AD-A284 311

AD

AD-E402 532

Technical Report ARAED-TR-94011

DESIGN TOOL FOR ARTILLERY SAFETY AND ARMING MECHANISMS CONTAINING CLOCK GEARS AND A STRAIGHT-SIDED VERGE RUNAWAY ESCAPEMENT AND OPERATING IN AN AEROBALLISTIC ENVIRONMENT

DTIC
SELECTE
SEP 07 1994
S D
F

F. R. Tepper, ARDEC
G. G. Lowen, City College of New York

August 1994

U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Armament Engineering Directorate

Picatinny Arsenal, New Jersey

Approved for public release; distribution is unlimted.

94-29155

DTIC QUALITY INSPECTED 3

94 9 06 215

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE August 1994	3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE

DESIGN TOOL FOR ARTILLERY SAFETY AND ARMING MECHANISMS CONTAINING CLOCK GEARS AND A STRAIGHT-SIDED VERGE RUNAWAY ESCAPEMENT AND OPERATING IN AN AEROBALLISTIC ENVIRONMENT

5. FUNDING NUMBERS

6. AUTHOR(S)

F. R. Tepper, ARDEC
G. G. Lowen, City College of New York

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSES(S) REPORT NUMBER

ARDEC, AED
Fuze Division (SMCAR-AEF-C)
Picatinny Arsenal, NJ 07806-5000

8. PERFORMING ORGANIZATION

Technical Report
ARAED-TR-94011

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(S) AGENCY REPORT NUMBER

ARDEC, IMD
STINFO Br (SMCAR-IMI-I)
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING

11. SUPPLEMENTARY NOTES

Parts of this material appeared originally in ARDC Technical Report ARLCD-CR-84003.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words) This investigation developed a computer simulation, which serves as a design tool for a complete safety and arming mechanism, which opperates in a projectile that experiences spin, precession, and nutation. This mechanism contains a straight-sided verge runaway escapement, a two-pass clock gear step-up train, and is powered by a spin-driven rotor. The mathematical model of the escapement recognizes three motion regimes, i.e., coupled motion, free motion, and impact. The model of the clock gear meshes differentiates between round-on-round and round-on-flat contact of the mating teeth.

The use as a design tool is furnished by the fact that the computer program allows an infinite variation in verge and rotor mass properties as well as in component center distances and clock tooth geometries with the circular arc and radial flank geometries. Similarly, the limits of operation of the mechanism when used in conjunction with a projectile having pathological aeroballistic motion may be observed.

14. SUBJECT TERMS

Clock gears, Safety and arming, Artillery, Escapement, M577 fuze, Fuze Verge escapement

15. NUMBER OF PAGES

369

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

CONTENTS

CONTENTS (cont)

INTRODUCTION

The present report describes the development of a computer simulation of a complete artillery safety and arming (S&A) mechanism, which must operate in a projectile that experiences spin, precession, and nutation. This mechanism consists of a straight-sided verge runaway escapement, a two pass step-up clock gear train and a spin-driven rotor.

Top views of the mechanism planes of the two possible configurations of this device are shown in figures 1 and 2, respectively. One of the feasible positions of this mechanism plane with respect to a projectile which experiences aeroballistic motion is given in figure 3.

The clock gear step-up meshes, whose kinematics and dynamics were developed in references 1 and 2, have been incorporated into the present verge type fuze simulation. It represents the latest fuze simulation work of the authors which began with the pin pallet escapement (ref 3). This initial effort was followed by a simulation of a complete S&A mechanism (ref 4) in which the motion of a spin-driven rotor is retarded by a pin pallet escapement that is driven through a involute gear train. The development of the dynamics of a straight-sided verge runaway escapement as well as the inclusion of this type of escapement into a S&A simulation where again a spin-driven rotor and an involute gear train are involved is given in reference 5. In both these computer models, the mechanisms experience only spin fields. In contrast, reference 6, which is the predecessor of the present work, represents for the first time a simulation of a S&A device with a verge type escapement and involute gears which operates in a full aeroballistic environment. The necessary background on the reverse kinematics of clock gear meshes was first stated in reference 7.

The kinematics of the aeroballistic system are described in appendix A, the angular momentum and its derivatives are given in appendix B, the absolute acceleration of the center of the S&A plane is provided in appendix C, the dynamics of the entire system are derived in appendix D, the projectile kinematics are discussed in appendix E, the kinematics of the clock gear meshes are shown in appendix F, the projectile kinematics in terms of a specific coordinate system is presented in appendix G, and the associated computer program is listed in appendix H.

GEOMETRY OF CLOCK GEAR TEETH AND KINEMATICS OF STEP-UP CLOCK GEAR TRAINS

The basic shape of a clock gear tooth, as used in the present work, consists of a circular arc or ogive type tip, which blends into a straight line (radial) flank that theoretically originates at the center of the gear blank. As in involute gearing, the intertooth spaces are designed such that there is sufficient clearance for a meshing set of clock gears. (Possible design methods are given by British Standard 978, Part 2, 1952: Gears for Instruments and Clockwork Mechanisms. Also see references 1 and 2.)

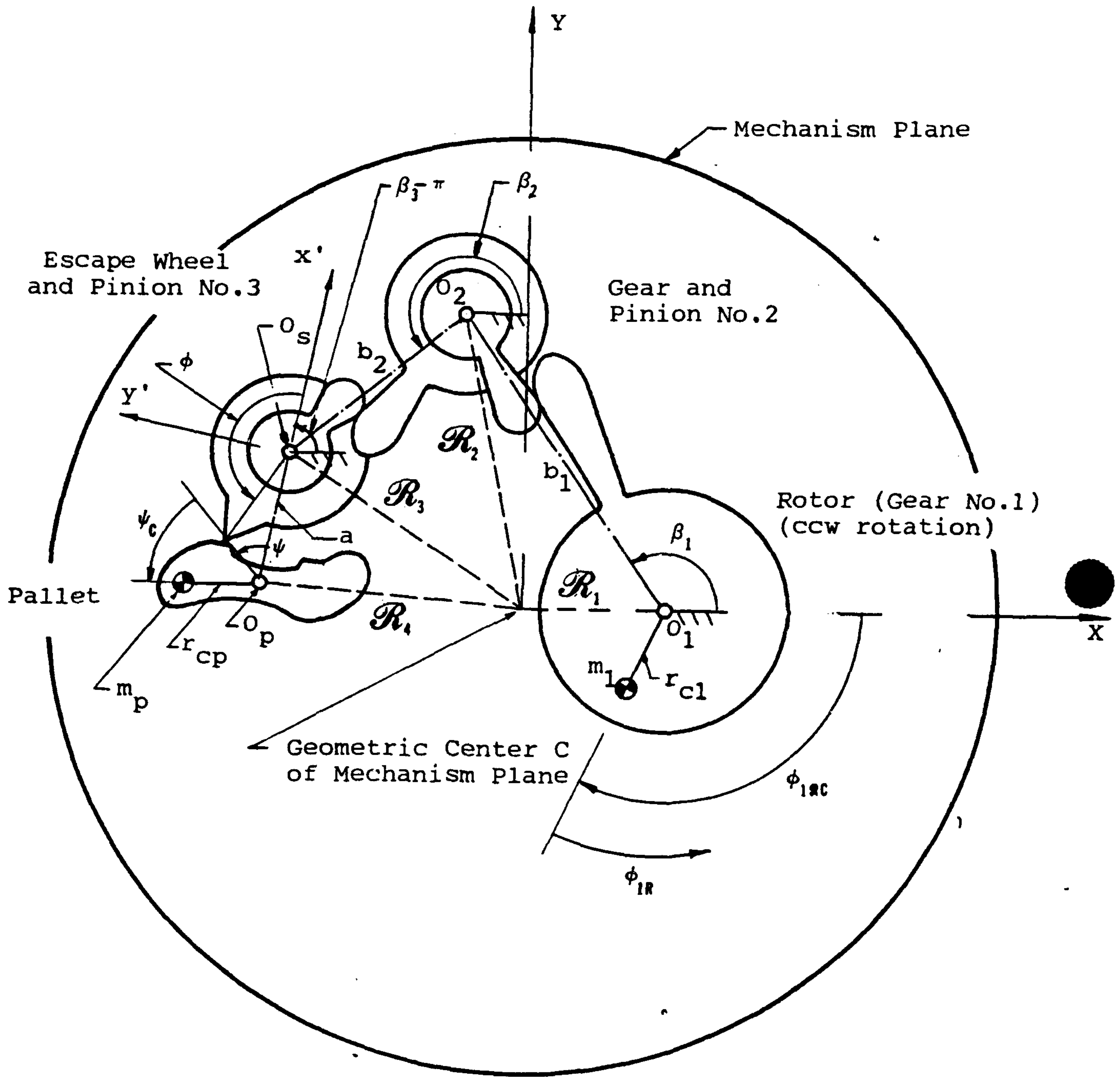


Figure 1. Rotor-driven S&A device with verge configuration no. 1

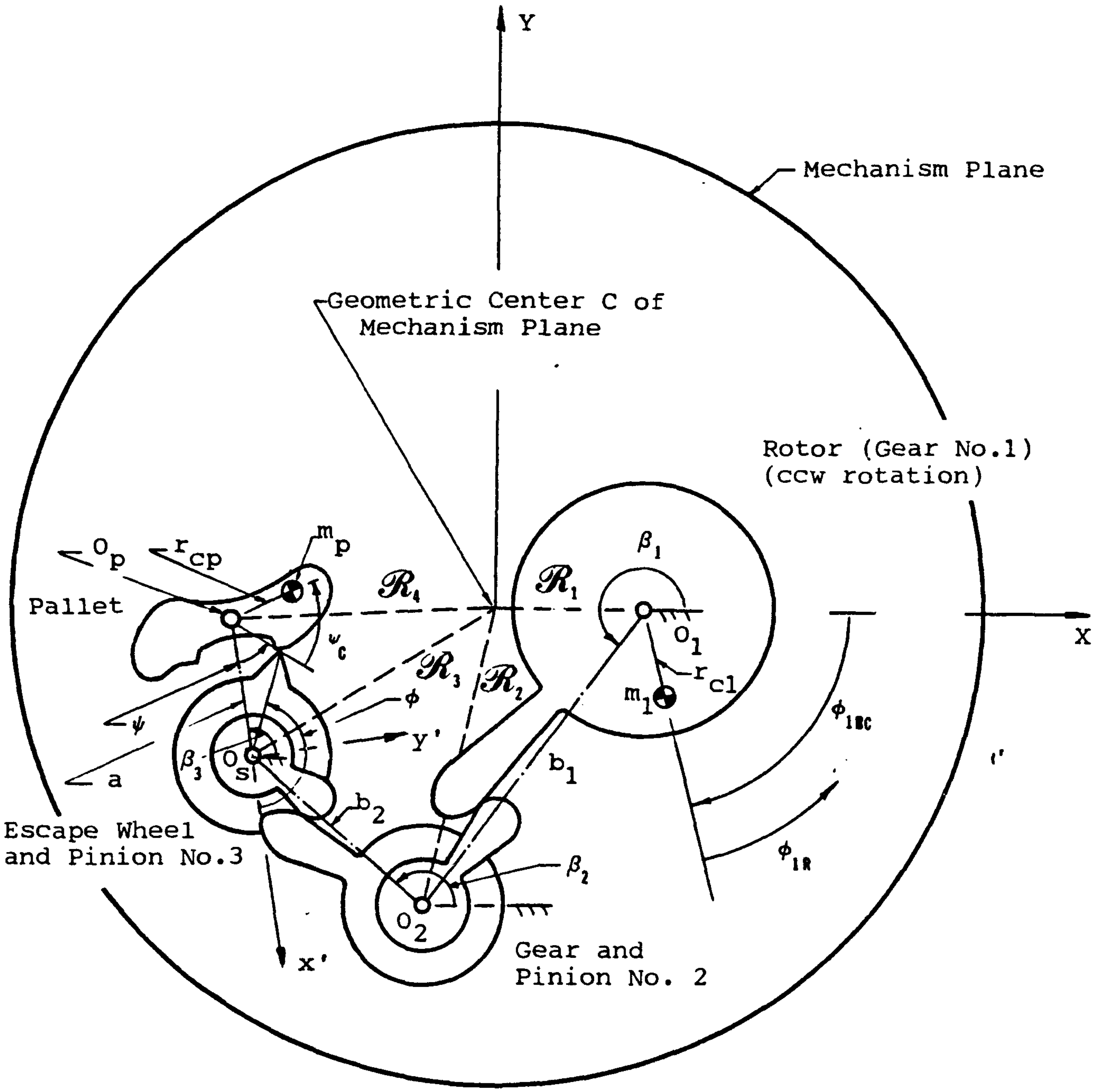


Figure 2. Rotor-driven S&A device with verge configuration no. 2

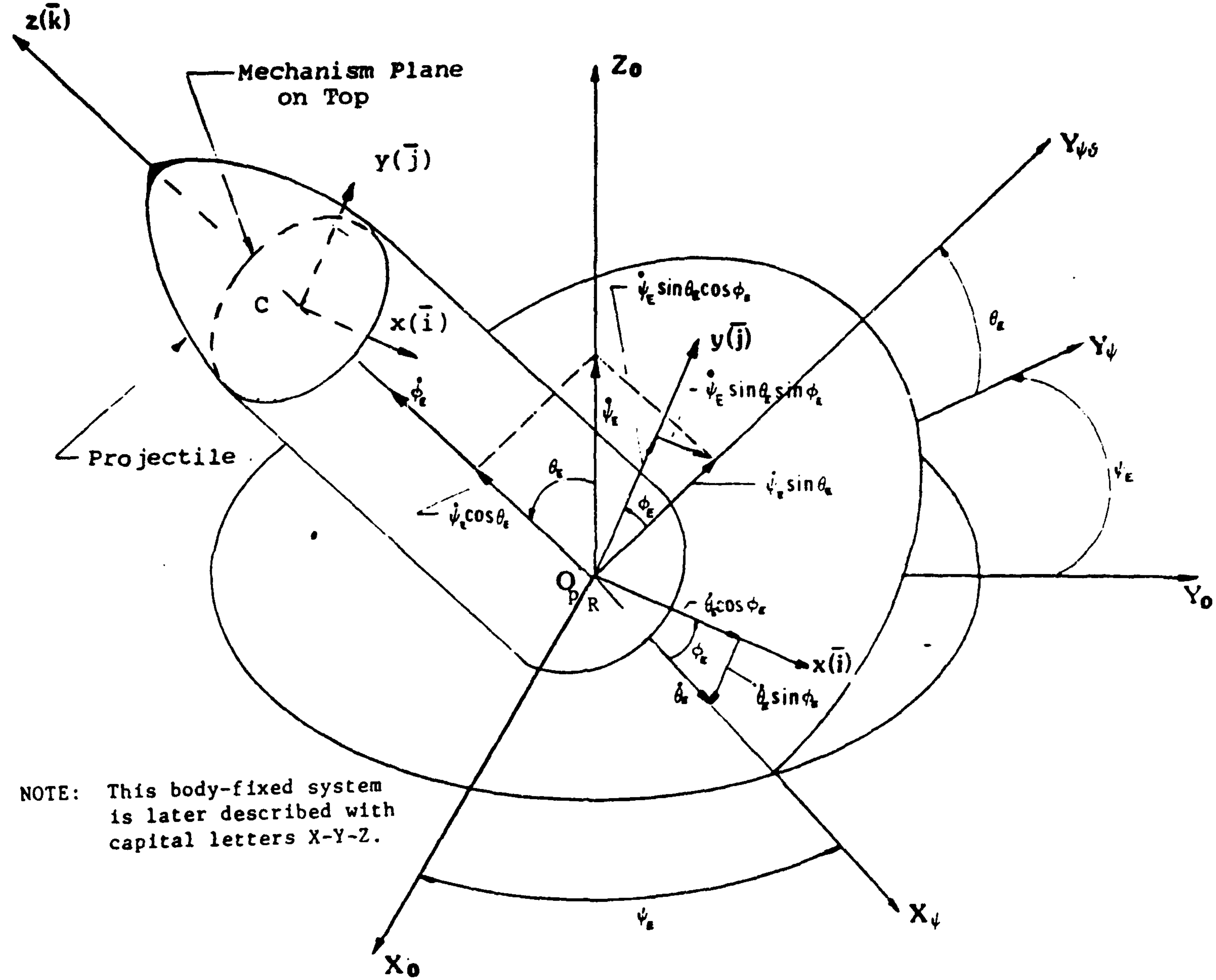


Figure 3. Mechanism plane in projectile which experiences aeroballistic motion

When meshed in step-up trains, where the gear drives the pinion, the initial contact is made between the circular arc tips of both components. This contract mode has been called round-on-round contact. As the motion continues, past a transition point on the pinion, the circular arc of the gear makes contact with the straight flank of the pinion. This contact mode has been designated as round-on-flat contact. During this regime the contact point between gear and pinion first proceeds inward with respect to the pinion flank. Subsequently, it moves outward and disengagement, i.e., transfer of motion to the next set of teeth occurs long before round-on-round contact could be reestablished. (Since the velocity ratio of such meshes is not constant, only one set of teeth can be in contact at any one time.)

The possible combinations of contact modes which arise cyclically in the two pass step-up clock gear trains shown in figures 1 and 2 are enumerated in table 1. Gear 1 and pinion 2 form mesh no. 1. The combination of gear 2 and pinion 3 is called mesh no. 2. (Note that the condition of mesh no. 2 always precedes that of mesh no. 1 in the chosen designations RR, FF, etc.)

Based on the work in references 1 and 7, appendix F of this report reviews and extends the development of the forward and reverse kinematics of meshes no. 1 and no. 2.

Besides input-output relationships as well as angular velocities and angular accelerations for both gear contact modes, expressions for transition angles and contact sensing equations are given. In addition, the angular velocities and accelerations of the rotor and the gear and pinion no. 2 assembly are derived in terms of the escape wheel angular velocity and acceleration for use in the final system differential equations.

Table 1. Possible contact mode combinations in a two pass step-up clock gear train

Train contact mode	Mesh no. 2 (gear 2 and pinion 3)	Mesh no. 1 (gear 1 and pinion 2)
RR	R	R
FF	F	F
RF	R	F
FR	F	R

NOTE: R = Round-on-round
F = Round-on-flat

DESCRIPTION OF COMPUTER PROGRAM AERCLOC

With the exception of the inclusion of both the kinematics and the dynamics of the clock gear meshes, the programming schemes which make it possible to distinguish between entrance and exit coupled motion, free motion, and impact of the verge escapement run parallel to those first given in reference 6. (It will also be helpful to consult the control details for the pin pallet escapement program, which were originally formulated in reference 3 and later adapted, without much change, to the verge escapement in reference 5). The main program starts with the reading and writing of all physical parameters of the S&A mechanism. Subsequently, subroutine GEAR, which has been written for clock teeth whose ogive centers of curvature lie off the tooth centerlines, provides the distances AG, together with the angles DELG, for both gears. It requires the input parameters CAPRP, CAPRO, RHOG, and TCG. (For explanation of terms, see Computer Simulation of Example Mechanism.)

Subroutine PINION has been written for clock teeth whose tip centers of curvature lie on the tooth centerline. It provides the distances AP and FP, as well as the angles DELP and ALPHP, for both pinions of the train. The needed input parameters are RP, RO, and RHOP. (The expressions used in the above subroutines were derived in references 1 and 2.)

To avoid confusion, it is to be noted that, RP2 and RO2 are the pitch and outside radii, respectively, of pinion no. 2 and belong to mesh no. 1. Similarly, RP3 and RO3 belong to the escape wheel pinion and are part of mesh no. 2. The pitch and outside radii of the rotor gear and gear no. 2 have the same numbers as the meshes they are associated with, i.e., CAPRP1 and CAPRO1, as well as CAPRP2 and CAPRO2, respectively.

The above is followed by the initialization of the escapement and gear contact forces in coupled and free motion, the computation of the sums of the individual mesh radii of curvature, as well as the center distances. Finally, before the clock gear transition angles are determined, the various fuze body angles are obtained (ref 4).

The simulation begins with entrance coupled motion at a starting angle PHID, which represents that angle ϕ of the escape wheel that is associated with the approximate center of the entrance working surface of the verge. This angle then corresponds to a cumulative escape wheel angle PHITOT of zero degree.

Preliminary Computations for Mesh No. 1

Determination of Transition Angles

The transition angle PH2PT = ϕ_{2PT} (app F., eq F-25) is established as that angle for which a small change in the direction of continued motion of the rotor angle PHI1 = ϕ_1 will cause the associated value of G1 = g_1 (eq F-18) to become smaller than its transition value FP1 = f_{p1}. Since the rotor gear no. 1 turns in a counterclockwise (ccw) direction, the above change in PHI1 must be positive.

The program accomplishes this task in the following manner:

1. The two possible transition angles PH2PT1 and PH2PT2 of pinion no. 2 are computed according to equation F-25 (app F).

2. Subroutine TRANS1, which is valid for meshes in which the input gear has ccw rotation, is called and the rotor transition angle PHI1T1, which is associated with the pinion transition angle PH2PT1, is computed according to equations F-29 and F-30 (app F).

3. The rotor angle PHI1T1 is made slightly larger to become PHINEX, and equation F-14 (app F) is used to find the associated pinion angle P2NEX. Since there are two such angles resulting from the computation, the subroutine must select that one which is closest to the pinion transition angle PH2PT1. Subsequently, the associated value of g_{11}, in the form of G11, is determined according to equation F-18 (app F).

4. After control is returned to the main program, the value of G11 is compared to that of the transition magnitude FP1. Assuming that G11 is smaller than FP1, the transition angles PH1T1 and PH2PT1 govern.

5. If that is not the case, steps 2 and 3 are repeated for the second transition angle of the pinion, i.e., PH2PT2. This results in the determination of G12.

6. Again, control is returned to the main program and G12 is now tested against FP1. If it is smaller than FP1, the transition angles PHI1T2 and PH2PT2 govern. If the test fails, the program is terminated with the message "SOMETHING IS WRONG WITH MESH 1".

Determination of Correct Sign for Forward Round-on-Flat regime of Mesh No. 1

The sign preceding the square root in equation F-14 (app F), for the forward round-on-flat contact mode of mesh no. 1, is determined with the help of the rotor gear transition angle PHI1T. Both possible pinion angles PH2PF1 and PH2PF2 are first determined. The sign used in the determination of the one which deviates least from the pinion transition angle PH2PT is then given to the signum function SIGN1F. This parameter is used throughout the program in conjunction with equation F-14 (app F).

Latest and Earliest Possible Values of PHI1 and PHI2P of Mesh No. 1

The latest and earliest values of the gear and pinion angles PHI1 AND PHI2P, respectively, are found by continuously evaluating the round-on-flat regime equation F-14 (app F) with SIGN1F, and simultaneously checking the contact condition for the subsequent set of clock teeth, as given by equation F-31 (app F). This loop is initiated at the transition angle PHI1T and it is terminated when the condition of equation F-31 (app F) is met. The latter furnished PHI1F the latest possible contact angle of the rotor gear, as well as PH2PFF, the latest possible contact angle of pinion 2. (These are the angles at which contact is transferred to the subsequent gear mesh.) To obtain the earliest possible (initial) contact angles PHI1I of the rotor and PH2PI of the pinion, the appropriate tooth spacing angles are added or subtracted, as needed, from the respective final contact angles. The initial rotor angle PHI1I is obtained by subtracting the gear tooth spacing angle DPHI1 from the final angle PHI1F. By adding the pinion tooth spacing angle DPHI1P to PH2PFF, the initial pinion contact angle PH2PI results.

Determination of Correct Sign for Forward Round-on-Round Regime of Mesh No. 1

The sign preceding the square root in equation F-1 (app F), for the round-on-round contact mode of mesh no. 1, is determined with the help of the initial rotor gear angle PHI1I. Both possible pinion contact angles PH2PR1 and PH2PR2 are first obtained. The sign used in the computation of that one which deviates least from the initial pinion contact angle PH2PI, is subsequently assigned to the signum function SIGN1R.

Reverse Kinematics of Mesh No. 1

Determination of Correct Sign for Reverse Round-on-Round Regime of Mesh No. 1. The sign preceding the square root in equation F-68 (app F), which allows the determination of the rotor gear angle for a given angle of the pinion during reverse round-on-round contact, is found with the help of the initial pinion angle PH2PI. Both possible rotor gear angles PHI1R1 and PHI1R2 are first computed. The sign used in the determination of that of the above angles, which deviates least from the associated initial rotor angle PHI1I is then assigned to the signum function RSGN1R.

Determination of Correct Sign for Reverse Round-on-Flat Regime of Mesh No. 1. The sign preceding the square root in equation F-95 (app F), which is used to determine the rotor gear angle for a given pinion angle during reverse round-on-flat contact, is found with the help of the final (latest) pinion contact angle PH2PFF. Both possible rotor gear angles PHI1F1 and PHI1F2 are first obtained. Subsequently, the sign used in the computation of that rotor gear angle which deviates least from the associated final rotor angle PHI1F is assigned to the signum function RSGN1F.

Preliminary Computations for Mesh No. 2

The general procedures for the preliminary computations for mesh no. 2 are identical to those that were followed for mesh no. 1. It must only be kept in mind that for mesh no. 2 the gear (i.e., gear 2) rotates clockwise, while the pinion (i.e., pinion 3, the escape wheel pinion) turns in a ccw direction.

Determination of Transition Angles

The transition angle PHIST = ϕ_{ST} (app F, eq F-59) is also established as that angle for which a small change in the direction of continued forward motion of the now applicable gear no. 2 angle PHI2 = ϕ_{2G} will cause the associated value of G2 = g_2 (app F, eq F-52) to become smaller than the flank transition value FP2 = f_{p2}. Since gear no. 2 turns in a clockwise direction, the above change in PHI2 must be negative. The program accomplishes this task in the following manner:

1. The two possible transition angles PHIST1 and PHIST2 of pinion no. 3 are computed according to equation F-59.

2. Subroutine TRANS2, which is valid for meshes in which the driving gear has CW rotation, is called and the gear no. 2 transition angle PHI2T1, which is associated with the pinion transition angle PHIST1, is computed according to equations F-63 and F-64.

3. The gear no. 2 angle PHI2T1 is made slightly smaller to become PHINEX, and equation F-48 (for round-on-flat contact) is used to find the associated escape wheel pinion angles PSNEX1 and PSNEX2. The subroutine must now select the one of the two which is closest to the pinion transition angle PHIST1. Subsequently, the associated value of G21 = g_{21} is determined according to equation F-52.

4. After control is returned to the main program, the value of G21 is compared to that of the transition magnitude FP2. Assuming that G21 is smaller than FP2, the transition angles PHI2T1 and PHIST1 govern.

5. If this is not the case, steps 2 and 3 are repeated for PHIST2, the second possible transition angle of the escape wheel pinion. This results in the determination of PH12T2 and G22.

6. Again, control is returned to the main program and G22 is now compared with FP2. If it is smaller than FP2, the transition angles PHI2T2 and PHIST2 govern. If the test is failed, the program is terminated with the message: "SOMETHING IS WRONG WITH MESH 2."

Determination of Correct Sign for Forward Round-on-Flat Regime of Mesh No. 2

The sign preceding the square root in equation F-48 (app F), for the forward round-on-flat contact mode of mesh no. 2, is determined with the help of the gear no. 2 transition angle PHI2T. Both possible angles PHISF1 and PHISF2 of pinion 3 are first computed. The sign employed in the determination of the angle which deviates least from the pinion transition angle PHIST is then assigned to the signum function SIGN2F. This parameter is subsequently used whenever there is need for equation F-48 (app F).

Latest and Earliest Possible Values of PHI2 and PHIS of Mesh 2

The latest and earliest values of the gear and pinion angles PHI2 AND PHIS, respectively, are found by continuously evaluating the forward round-on-flat regime equation F-48 (app F) with SIGN2F and simultaneously checking the contact condition for the subsequent set of teeth, as given by equation F-65 (app F). This loop is initiated at the transition angle PHI2T and it is terminated when the condition of equation F-65 (app F) is met. (Note that the increments of angle PHI2 are negative, since gear no. 2 advances in the clockwise direction.) The latter furnished PHI2F, the latest possible contact angle of the gear, as well as PHISFF, the latest possible contact angle of pinion no. 3. Again, these are the angles at which contact is transferred to the subsequent gear mesh. To obtain the earliest possible (initial) contact angles PHI2I of the gear no. 2 and PHISI of pinion no. 3, the appropriate tooth spacing angles are again added or subtracted, as needed, from the final contact angles. The initial angle PHI2I of gear no. 2 is obtained by adding the tooth spacing angle DPHI2 to the final angle PHI2F. (The gear rotates clockwise and the subsequent tooth centerline is at a larger angle with respect to the reference axis than the preceding one.) By subtracting the pinion tooth spacing angle DPHIS from the final angle PHISFF, the initial pinion no. 3 contact angle PHISI results. (The pinion rotates ccw and the subsequent tooth centerline is at a smaller angle with respect to the reference axis than the preceding one.)

Determination of Correct Sign for Forward Round-on-Round Regime of Mesh No. 2

The sign preceding the square root in equation F-34 (app F), for the forward round-on-round contact mode of mesh no. 2, is determined with the help of the initial angle PHI2I. Both possible pinion no. 3 angles PHISR1 and PHISR2 are first obtained. Subsequently, the sign used in the determination of the angle which deviates least from the initial pinion no. 3 angle PHISI is assigned to the signum function SIGN2R.

Reverse Kinematics of Mesh No. 2

Determination of Correct Sign for Reverse Round-on-Round Regime of Mesh No. 2. The sign preceding the square root in equation F-113 (app F), which allows the determination of the gear no. 2 angle for a given angle of pinion no. 3 during reverse round-on-round contact, is found with the help of the initial pinion angle PHISI. Both possible angles PHI2RI and PHI2R2 of gear no. 2 are first computed. Subsequently, the sign used in the determination of that angle, which deviates least from the associated initial gear angle PHI1I, is assigned to the signum function RSGN2R.

Determination of Correct Sign for Reverse Round-on-Flat Regime of Mesh No. 2. The sign preceding the square root in equation F-131 (app F), which is used to determine the angle of gear no. 2 for a given angle of pinion no. 3 during reverse round-on-flat contact, is found with the help of PHISFF, the final contact angle of pinion no. 3. Both possible angles PHI2F1 and PHI2F2 of gear no. 2 are first obtained. Subsequently, the sign used in the computation of that gear angle which deviates least from the final gear no. 2 angle PHI2F, is assigned to the signum function RSGN2F.

Data for Runge-Kutta

The program made use of the existing fourth order Runge-Kutta routine RKGS for the solution of all differential equations[1].

The initial statements make it possible to start the mechanism simulation with both gear meshes at arbitrary positions between their earliest and latest contact angles. To this end, the proportionality factors J1 and J2, which may be set from zero to unity, are introduced to obtain the pinion starting angles PHI2P and PHIS of meshes no. 1 and no. 2, respectively.

[1]IBM System/360 Scientific Subroutine Package (360A-CM-OX3), Version III.

To devise an appropriate expression for mesh no. 1, consider that pinion no. 2 always turns clockwise as the rotor advances. Because of this fact, the pinion angle PH2PFF, which is associated with the latest possible mesh contact, is always more negative (minus five degrees is more negative than minus one degree) than PH1PI, the pinion angle associated with the earliest possible contact. Similarly, all possible starting angles of pinion no. 2 must either be equal to or more negative than PH2PI. With this reasoning, the difference between the latest and earliest possible contact angles of pinion no. 2, i.e.,

$$\text{DIFF1} = \text{PH2PFF} - \text{PH2PI} \tag{1}$$

will always be negative, regardless of the signs of the two angles. Further, together with J1, any arbitrary starting angle of pinion no. 2 will be correctly described by

$$\text{PH12P} = \text{J1} * \text{DIFF1} + \text{PH2PI} \tag{2}$$

The expression for the starting angle PHIS of mesh 2 is based on the fact that the escape wheel pinion no. 3 always turns in the ccw direction. Therefore, any pinion angle, associated with contact after the earliest contact angle PHISI, will be larger (more positive) than PHISI. With this reasoning, the difference between the latest and earliest possible contact angles, i.e.,

$$\text{DIFF2} = \text{PHISFF} - \text{PHISI} \tag{3}$$

will always be positive, regardless of the signs of the two angles. Then, together with J2, the arbitrary starting angle of pinion no. 3 will be correctly given by:

$$\text{PHIS} = \text{J2} * \text{DIFF2} + \text{PHISI} \tag{4}$$

The starting conditions for coupled motion are as follows:

1. The initial angle PHID of the escape wheel, i.e., the Runge-Kutta variable PHI(1), equals 139 degrees (read in as part of data).

2. The initial angular velocity of the escape wheel, i.e., the Rung-Kutta variable PHI(2), equals zero.

3. The verge angle ALPHA = α equals ALPHEN = α_{en}, for entrance, in distinction from the exit verge angle ALPHEX = α_{ex} (ref 5).

Coupled Motion

With the four possible gear contact modes, the coefficients of the governing differential equations of coupled motion must change accordingly. The general form of this expression is given by

$$W_1\ddot{\phi} + W_2\dot{\phi}^2 + W_3\dot{\phi} = W_4 + W_5(O_x \sin\gamma - O_y \cos\gamma) + W_6(K_x \sin\beta - K_y \cos\beta) \qquad (5)$$

where $\phi(t)$ represents the escape wheel angle PHI(1).

The applicable subscripts of the A_j's which correspond to the W_i's as well as the equation numbers of the associated differential equations for the four gear contact mode are given in table 2.

The difference between entrance and exit coupled motion is expressed by the value of the signum function s_7. This becomes crucial for the computations of the factors A_{16}, A_{21}, A_{29}, A_{36}, and A_{51}[2].

Table 2. Coefficients of equation 5 for the coupled motion differential equations of the four gear train contact modes

Gear train contact mode	RR	FF	RF	FR
Governing differential equation	D-949	D-974	D-997	D-1020
W_1	A_{105}	A_{120}	A_{134}	A_{148}
W_2	A_{106}	A_{121}	A_{135}	A_{149}
W_3	A_{107}	A_{122}	A_{136}	A_{150}
W_4	A_{108}	A_{123}	A_{137}	A_{151}
W_5	A_{109}	A_{124}	A_{138}	A_{152}
W_6	A_{110}	A_{125}	A_{139}	A_{153}

[2]The program uses the symbol AA1, etc., throughout. This should not be confused with the symbols AA_{16} to AA_{51}, which are first used in the combined exit coupled motion differential equation D-372 (app D).

To solve the applicable form of equation 5, the program calls on the Runge-Kutta subroutine FCT. The principal purpose of this subroutine is to present the relevant form of a second order differential equation in terms of two first order ones to RKGS. Subroutine OUTP is responsible for preparing the results of various computations for printing.

The individual forms of equation 5 are chosen with the help of the following control criteria shown in table 3.

Table 3. Control criteria

RR gear train contact mode	
PHI2 > PHI2T	Mesh no. 2
PHI1 < PHI1T	Mesh no. 1
FF gear train contact mode	
PHI1 < PHI2T	Mesh no. 2
PHI1 > PHI1T	Mesh no. 1
RF gear train contact mode	
PHI2 > PHI2T	Mesh no. 2
PHI1 > PHI1T	Mesh no. 1
FR gear train contact mode	
PHI2 < PHI2T	Mesh no. 2
PHI1 < PHI1T	Mesh no. 1

Before discussing the details of subroutine FCT and subroutine OUTP, it is necessary to point out the manner in which each step of the integration, relates to the increase in the escape wheel pinion angle PHIS, as well as to the determination of cumulative escape wheel angle PHITOT. (Since the escape wheel angle varies between approximately 134 and 144 degrees during entrance coupled motion, and between approximately 209 and 216 degrees during exit coupled motion, PHITOT can only be obtained by continuously adding the increment in PHI(1) due to each cycle of computation.) The procedure of obtaining the angle γ of the rotor center of mass will be shown in connection with the description of subroutine GKINEM. The verge center of mass angle β is given in FCT with the help of subroutine KINEM.

Subroutine OUTP starts with the definition of the increment DELPHI of the escape wheel angle PHI(1):

$$DELPHI = PHID - PHIPR \tag{6}$$

where

PHID = the current value of PHI(1), as obtained after each round of integration

PHIPR = the value of PHI(1) obtained in the previous integration, or from the initial condition of this angle

Once DELPHI is determined, the cumulative escape wheel angle PHITOT can be incremented by this amount. Since the incremental rotation of pinion no. 3 must be identical to that of the escape wheel, the increment DDPHIS of PHIS is equal to DELPHI, and the cumulative pinion angle is obtained by

$$PHIS = PHIS + DDPHIS \tag{7}$$

It is to be noted that, for computing all initial quantities, such as contact forces, at T = 0, as well as for setting up the various values for the first round of integration, both DELPHI and DDPHIS are zero, since PHI(1) and PHIPR have the same value of the starting escape wheel angle.

As a consequence of the first and all subsequent integrations, DELPHI will always be a positive quantity.

Subroutine FCT. The computations for all the parameters, associated with the various forms of the coupled motion differential equation are made in FCT in terms of the current values of the escape wheel variables PHI(1) and PHI(2), as well as the escape wheel pinion angle PHIS. To accomplish some of this, FCT calls on other subroutines as needed. The following outlines all computations in FCT in a sequential manner:

1. Subroutine KINEM is called to compute the current values of the escapement variables PSI = ψ, G = g, DPSI = $\dot{\psi}$ and VST = $V_{S/T}$. In addition, the moment arms AONE = A_1' to DONE = D_1' are obtained (ref 5). The above makes it possible to determine angle BETA = β in FCT.

2. Subroutine AFIVE is called.

a. Subroutine ACCEL is called for the determination of the absolute accelerations of the pivot points of the individual train components.

b. Subroutine GKINEM is called. It deals with the determination of the reverse kinematics of meshes no. 1 and 2, as defined in appendixes F-III and F-IV, respectively. Starting with mesh no. 2, which now has the angle PHIS = ϕ_s, the angular velocity PHI(2) = $\dot{\phi}$ and the angular acceleration $\ddot{\phi}$ of the escape wheel pinion as the inputs, the following output related variables are determined:

<u>Round-on-round contact</u>

PHI2 = ϕ_{2G}	(eq F-104)
LAMDA2 = λ_2	(eq F-38 and F-39)
DER2R	(eq F-109)
PHDOT2 = $\dot{\phi}_{2G}$	(eq F-108)
VST2R = $V_{S2/T2R}$	(eq F-47)
X7, X8, X9, Y5, Y6 used to determine $\ddot{\phi}_{2G}$	(eq F-114 to F-118)

<u>Round-on-flat contact</u>

PHI2 = ϕ_{2G}	(eq F-122)
G2 = g_2	(eq F-52)
DER2F	(eq F-127)
PHDOT2 = $\dot{\phi}_{2G}$	(eq F-126)
VST2F = $V_{S2/T2F}$	(eq F-58)
X10, X11, X12, Y7, Y8 used to determine $\ddot{\phi}_{2G}$	(eq F-132 to F-136)

Subsequently, parallel values are determined for mesh no. 1. Now PHI2 and PHDOT2, as well as $\ddot{\phi}_{2G}$, of pinion no. 2 are the inputs, while PHI1 = ϕ_1, PHDOT1 = $\dot{\phi}_1$ and $\ddot{\phi}_1$ of gear 1 are the outputs. The incremental angle DDPHI1 and the total angle PHI1TOT, both of gear no. 1, are defined. This allows the determination of the angle GAM = γ.

c. The signum functions S4, S5, and S7 are computed.

d. Subroutine AWON is called for the computation of AA1 to AA23.

e. Subroutine CWON is called for computation of CC1 to CC20.

f. Subroutine ATWO is called for the computation of AA24 to AA42.

g. Subroutine CTWO is called for the computation of CC21 to CC36.

h. Subroutine ATHREE is called for the computation of AA43 to AA71.

i. Subroutine CTHREE is called for the computation of CC37 to CC56.

j. Subroutine AFOUR is called for the computation of AA72 to AA93.

k. Subroutine CFOUR is called for the computation of CC57 to CC72.

l. The parameters AA94 to AA132 are computed.

3. Subroutine ASIX is called by FCT. ASIX calls sequentially on subroutines ACCEL, GKINEM, and again computes S4, S5, and S7. Subsequently, it calls also on AWON, CWON, ATWO, CTWO, ATHREE, CTHREE, AFOUR, and CFOUR. The above are necessary for the further computation of AA133 to AA177.

4. Control is returned to FCT, a· ! depending on the gear contact mode, the appropriate differential equation is chosen in the manner of tables 2 and 3.

5. The applicable second order coupled motion differential equation is now presented in terms of the following two first order ones for subsequent numerical solutions:

$$\mathrm{DPHI(1) = PHI(2)} \qquad : (=\dot{\phi}) \tag{8}$$

$$\mathrm{DPHI(2) = 1/W1*(-W2*PHI(2)**2 - W3*PHI(2) + W4}$$

$$\mathrm{+ W5*(OX*SG - OY*CG) + W6*(KX*SB - KY*CB))} \quad : (=\ddot{\phi}) \tag{9}$$

Note that because many of the CC and AA parameters are independent of gear tooth geometry and thus do not change with tooth contact mode, the extra identifiers R or F used in the subscripts of the various derivations have been omitted in Program AERCLOC.

Subroutine OUTP. Subroutine OUTP prepares the step by step solution values of PHI(1), PHI(2), PSI (verge angle), DPSI (verge angular velocity), G (contact length on verge), PHITOT, as well as all contact forces for printing. Further, it determines the maximum values of these contact forces during one arming cycle. Finally, it performs a test for continued coupled motion by making sure that G is larger than zero for entrance coupled motion and negative for exit coupled motion (ref 5). In addition the contact force P_n must not vanish.

This is accomplished in the following sequence:

1. PHITOT and PHIS are incremented.

2. Subroutine KINEM is called.

3. Subroutine AFIVE is called.

4. Subroutine ASIX is called.

5. The appropriate contact forces are computed.

6. Output is printed.

7. Tests for continued coupled motion are performed.

Free Motion

The differential equations of free motion, i.e., that of the verge, as given by equation D-1038 (app D) and those for the four gear contact modes of the escape wheel - gear train - rotor system are again solved by way of a Runge-Kutta routine.

To account for the gear contact modes, the latter takes the following general form:

$$Z_1\ddot{\phi} + Z_2\dot{\phi}^2 + Z_3\dot{\phi} + Z_4 = 0 \quad , \tag{10}$$

where $\phi(t)$ again represents the escape wheel angle.

The applicable subscripts of the A_j's which correspond to Z_j's as well as the equation numbers of the associated differential equations are given in table 4.

Table 4. Coefficient of equation 10 for the free motion differential equations of the escape wheel - gear train - rotor system

Gear train contact mode	RR	FF	RF	FR
Governing differential equation	D-1040	D-1048	D-1056	D-1064
Z_1	A_{162}	A_{166}	A_{170}	A_{174}
Z_2	A_{163}	A_{167}	A_{171}	A_{175}
Z_3	A_{164}	A_{168}	A_{172}	A_{176}
Z_4	A_{165}	A_{169}	A_{173}	A_{177}

The individual forms of equation 10 are again chosen with the help of the control criteria given earlier in table 2. To solve the applicable set of differential equations, i.e., equation D-1038 (app D) and equation 10, the program calls on the Runge-Kutta subroutine FCTF. This routine presents the relevant forms of the two second order differential equations in terms of four first order ones to RKGS. Subroutine OUTPF is responsible for preparing the results of the various computations for printing. The cumulative escape wheel angle PHITOT is computed in a manner similar to that described earlier for coupled motion.

Subroutine FCTF

The computations for all the parameters, associated both with the independently moving verge and the escape wheel - gear train - rotor system, are made in terms of the current values of the verge variables ψ and $\dot{\psi}$ as well as the escape wheel variables ϕ and $\dot{\phi}$. To accomplish this, FCTF, like FCT before, calls on other subroutines as needed.

The following outlines all computations in FCTF in a sequential manner:

1. Subroutine AFIVE is called.

a. Subroutine ACCEL is called for the determination of the absolute accelerations of the pivot points of the individual train components.

b. Subroutine GKINEM is called to evaluate, in the same manner as for coupled motion, all variables associated with the reverse kinematics of meshes 1 and 2. Thus, with the escape wheel position, velocity and acceleration known, the same type of kinematic values are determined for gear and pinion no. 2 as well as the rotor.

Subsequently, steps 2c and 2l, 3, and 4 of FCT are performed, as applicable. (While the control criteria of table 3 remain, the coefficients of table 4 are used for obtaining the appropriate expressions for equation 10.)

To obtain the magnitude of the variables ϕ and ψ, as well as their derivatives at identical times, the two independent second order differential equations are transformed into four simultaneous first order ones.[3] (While actually only the two first order equations, associated with each of the two variables are coupled, the routine treats all four as if they were coupled and, therefore, produces solutions for identical time increments.)

[3]Note that whenever $I_{PR} \leq 0$, the simulation terminates.

These four expressions have the following form in FCTF:

$$DX(1) = X(2) : (=\dot{\phi}) \tag{11}$$

$$DX(3) = X(4) : (=\dot{\psi}) \tag{12}$$

$$DX(2) = 1/Z_1*(-Z_2 * X(2)**2 - Z_3 * X(2) - Z_4) : (=\ddot{\phi}) \tag{13}$$

$$DX(4) = \frac{1}{I_{PR}} * [-A_{32} * X(4)**2 - A_{31} * X(4) - A_{119} + m_p * r_{cp} * (K_x * SB - K_y * CB)] : (=\ddot{\psi}) \tag{14}$$

The note at the end of subroutine FCT also holds for subroutine FCTF.

Subroutine OUTPF

Subroutine OUTPF prepares the step by step solution values of PHI(1), the escape wheel angle, PHI(2), the escape wheel velocity, PSI (verge angle), DPSI (verge velocity), and PHITOT, as well as the gear contact forces for printing. Further, it determines the maximum values of these contact forces. Finally, it performs a test for continued free motion by computing the normal and tangential distances F and GP, respectively, of the tip of the escape wheel from the working surface of the verge. The signs of these parameters are different for entrance and exit free motion (ref 5).

This is accomplished in the following sequence:

1. PHITOT and PHIS are incremented.
2. Subroutine AFIVE is called.
3. Subroutine ASIX is called.
4. The gear contact forces associated with free motion are computed.
5. Output is printed.
6. Tests for continued free motion are performed.

Impact

Subroutine IMPACT uses the pre-impact values $\dot{\phi}_i$ and $\dot{\psi}_i$ of the angular velocities and computes their post-impact values $\dot{\phi}_f$ and $\dot{\psi}_f$ according to equations D-1071 and D-1072, respectively.

The value of the total moment of inertia ISTOT of the combined escape wheel - gear train - rotor system, as referred to the escape wheel axis, depends on the gear train contact mode and is chosen with the help of the control criteria of table 3. (See also equations D-1073 to D-1076.)

Reversal of Gear Train Motion Due to Impact

If the impact torque on the escape wheel is sufficiently large, the motion of the gear train may be temporarily reversed; i.e., the escape wheel angular velocity $\dot{\phi}$ may become negative. This would cause the friction forces between the gear teeth and at the various gear pivots to be reversed in direction. (The normal forces between the gear teeth remain unaffected, and the normal bearing forces are obtained in the usual manner.) This change in the direction of the friction forces is expressed for both coupled and free motion by letting the coefficient of friction μ of all gear train components become negative (app E or ref 3). This is accomplished in subroutines AFIVE and ASIX by the following use of the signum function:

$$MU = ABS\,(MU) * \dot{\phi} / |\dot{\phi}| \qquad (15)$$

(The coefficient of friction associated with the escapement interface and the pallet pivot is called μ_1 and is read into the programs as MU1.) Any motion reversal at these surfaces is accounted for by the signum functions s_4 and s_5, respectively.

Termination of Computations

Computations are terminated whenever the geared motion of the rotor ends. This corresponds to ϕ = PHICUTD. The duration of the subsequent unretarded motion of the rotor is assumed to be negligible.

COMPUTER SIMULATION OF EXAMPLE MECHANISM

The simulated mechanism is that of the S&A device of the M577 fuze. It has configuration 2 (fig. 2) and is attached to the underside of the mechanism plane as shown by figures D-1 (app D) and G-1 (app G).

The clock-type gear and pinion parameters were obtained with the help of the clock gear formulae given in references 1 and 2. (See subroutines GEAR and PINION, respectively, in program AERCLOC.)

Computer program AERCLOC was run with a basic spin velocity of 30,000 rpm to obtain maximum contact forces. It used the projectile kinematics derived in appendix B (ref 6), which expresses both precession and nutation as predetermined percentages of spin.

The following shows the input requirements of the program, explains the various output data, and discusses the manner in which the number-of-turns-to-arm is obtained for a given spin velocity.

Input Data

The first portion of the output repeats all input data, which represent the mechanism parameters of the M577 S&A. These are listed both as computer variables and a symbols, according to the various appendixes of this report as well as of references 1, 2, 5, and 6.

Escapement Parameters

A = a = 0.226 in. = distance between pivots O_p and O_s (fig. 2)

B = b = 0.1685 in. = escape wheel radius

C = c = 0.132 in. = pallet radius as defined by figure F-1 of appendix F, reference 5

ALPHEN = α_{en} = 44.0056 deg = entrance working surface angle

ALPHEX = α_{ex} = 28.8277 deg = exit working surface angle

NT = 4 = number of escape wheel teeth spanned by verge

CONFIG = 2 = configuration no. 2 (fuze body configuration no. 2 in ref 5, app B)

EREST = e_r = 0 = coefficient of restitution

LAMBDA = = 91.9887 deg = angle between entrance and exit pallet radii (ref 5, app F, fig. F-1)

N = 22 = number of escape wheel teeth

For details of the above nomenclature, see reference 5, appendixes C, E, and F.

Clock Gear and Pinion Parameters

NG1 = 41 = number of teeth of total pitch circle of rotor gear no. 1

NG2 = 29 = number of teeth of gear no. 2

NP2 = 6 = number of teeth of pinion no. 2

NP3 = 6 = number of teeth of escape wheel pinion

CAPRP1 = R_{p1} = 0.46585 in. = pitch radius of rotor gear no. 1

CAPRP2 = R_{p2} = 0.22835 in. = pitch radius of gear no. 2

RP2 = r_{p2} = 0.06815 in. = pitch radius of pinion no. 2

RP3 = r_{p3} = 0.04725 in. = pitch radius of escape wheel pinion

CAPRO1 = R_{o1} = 0.4956 in. = outside radius of rotor gear no. 1

CAPRO2 = R_{o2} = 0.2486 in. = outside radius of gear no. 2

RO2 = r_{o2} = 0.08575 in. = outside radius of pinion no. 2

RO3 = r_{o3} = 0.0595 in. = outside radius of escape wheel pinion

RHOG1 = ρ_{G1} = 0.044 in. = radius of circular arc on tooth of rotor gear no. 1

RHOG2 = ρ_{G2} = 0.030 in. = radius of circular arc on tooth of gear no. 2

RHOP1 = ρ_{p1} = 0.0176 in. = radius of circular arc on tooth of pinion no. 2

RHOP2 = ρ_{p2} = 0.0122 in. = radius of circular arc on tooth of escape wheel pinion

TCG1 = t_{CG1} = 0.035 in. = circular tooth thickness at pitch circle of rotor tooth of gear no. 1

TCG2 = t_{CG2} = 0.024 in. = circular tooth thickness at pitch circle of tooth of gear no. 2

R1 = $\Re_1$ = 0.22539 in. = distance of rotor pivot from spin axis

R2 = $\Re_2$ = 0.408 in. = distance of pivot of gear and pinion no. 2 from spin axis

R3 = $\Re_3$ = 0.3685 in. = distance of pivot of escape wheel from spin axis

R4 = $\Re_4$ = 0.3881 in. = distance of pivot of pallet from spin axis

RHO1 = ρ_1 = 0.0465 in. = pivot radius of rotor

RHO2 = ρ_2 = 0.0225 in. = pivot radius of gear and pinion no. 2

RHO3 = ρ_3 = 0.0165 in. = pivot radius of escape wheel

RHOF1 = ρ_{F1} = 0.054 in. = friction thrust radius of rotor (for computation of friction thrust radius see p. 268 of ref. 10)

RHOF2 = ρ_{F2} = 0.027 in. = friction thrust radius of gear and pinion no. 2

RHOF3 = ρ_{F3} = 0.020 in. = friction thrust radius of escape wheel and pinion no. 3

RHOF = ρ_F = *0.018 in. = friction thrust radius of verge*

Mass Parameters of Components

M1 = m_1 = 0.3851 x 10^{-4} lb-sec^2/in. = mass of rotor

M2 = m_2 = 0.385 x 10^{-5} lb-sec^2/in. = mass of gear and pinion no. 2

M3 = m_3 = 0.2592 x 10^{-5} lb-sec^2/in. = mass of escape wheel and pinion no. 3

MP = m_p = 0.2982 x 10^{-5} lb-sec^2/in. = mass of pallet

IXX1 = $I_{\xi\xi_1}$ = 0.1748 x 10^{-5} in.-lb-sec^2 = moment of inertia of rotor with respect to an axis parallel to ξ_1-axis through center of mass (fig. A-3), but located in midplane between bearing plates (origin at pivot axis[4])

IEE1 = $I_{\eta\eta_1}$ = 0.2324 x 10^{-5} in.-lb-sec^2 = moment of inertia of rotor with respect to an axis parallel to η_1-axis through center of mass, but located in midplane[4]

IZZ1 = $I_{\zeta\zeta_1}$ = 0.3462 x 10^{-5} in.-lb-sec^2 = moment of inertia of rotor with respect to pivot axis (ζ_1-axis[4])

IXE1 = $I_{\xi\eta_1}$ = -0.4256 x 10^{-6} in.-lb-sec^2 = ξ_1-η_1 product of inertia of rotor with respect to above axes

IZX1 = $I_{\zeta\xi_1}$ = -0.3446 x 10^{-6} in.-lb-sec^2 = ζ_1-ξ_1 product of inertia or rotor with respect to above axes

IEZ1 = $I_{\eta\zeta_1}$ = -0.0402 x 10^{-6} in.-lb-sec^2 = η_1-ζ_1 product of inertia of rotor with respect to above axes

IX2 = I_{x2} = 0.0426 x 10^{-6} in.-lb-sec^2 = moment of inertia of gear and pinion no. 2 (about axis normal to pivot axis in midplane)

IY2 = I_{y2} = 0.0426 x 10^{-6} in.-lb-sec^2 = moment of inertia of gear and pinion no. 2 (about axis normal to pivot axis and perpendicular to x_2-axis)

IZ2 = I_{z2} = 0.4031 x 10^{-7} in.-lb-sec^2 = moment of inertia of gear and pinion no. 2 with respect to pivot axis

[4]The intersection of the various pivot axes and the aforementioned midplane furnishes the origins for all component moment equations. (See also the moment arms $L_U = L_L$ below.)

IXS = I_{xs} = 0.3094 x 10^{-7} in.-lb-sec^2 = moment of inertia of escape wheel and pinion no. 3 (about axis normal to pivot axis in midplane)

IYS = I_{ys} = 0.3094 x 10^{-7} in.-lb-sec^2 = moment of inertia of escape wheel and pinion no. 3 (about axis normal to pivot axis and perpendicular to x_s-axis)

IZS = I_{zs} = 0.1639 x 10^{-7} in.-lb-sec^2 = moment of inertia of escape wheel and pinion no. 3 with respect to pivot axis

IXXP = $I_{\xi\xi_p}$ = 0.6286 x 10^{-7} in.-lb-sec^2 = moment in inertia of pallet with respect to an axis parallel to ξ_p-axis through center of mass (fig. A-2), but located in midplane, with origin at the pivot axis

IEEP = $I_{\eta\eta_p}$ = 0.4827 x 10^{-7} in.-lb-sec^2 = moment of inertia of pallet with respect to an axis parallel to η_p-axis through center of mass, but located in midplane

IZZP = $I_{\xi\xi_p}$ = 0.7173 x 10^{-7} in.-lb-sec^2 = moment of inertia of pallet with respect to above pivot axis (ζ_p-axis)

IXEP = $I_{\xi\eta_p}$ = 0.2813 x 10^{-7} in.-lb-sec^2 = product of inertia of pallet with respect to above axes

IEZP = $I_{\eta\zeta_p}$ = 0.0 = product of inertia of pallet with respect to above axes

IZXP = $I_{\zeta\xi_p}$ = 0.0 = product of inertia of pallet with respect to above axes

General Parameters

RC1 = r_{c1} = 0.100 in. = distance from pivot axis of rotor to its center of mass

RCP = r_{cp} = 0 = distance from pivot axis of verge to its center of mass

RHOP = ρ_p = 0.0140 in. = pallet pivot radius

RPM = 30,000 = spin rate

PHI1RCD = ϕ_{1RC} = -113.12 deg = rotor angle in starting position (fig. 2)

PSICCD = ψ_c = 0 deg = eccentricity angle of pallet

PHID = 141 deg = escape wheel starting angle of initial entrance coupled motion

PHICUTD = 1595 deg = cumulative escape wheel angle obtained from product of total engaged rotor rotation and gear ratio. The total rotor rotation for the M577 fuze is 48.292 deg while the nominal gear ratio equals 41 x 29/36 = 33.03. Thus, PHICUTD = 48.292 x 33.03 = 1595 deg. (With 5.5 circular pitches, the rotor rotation becomes 5.5 x 360/41 = 48.292 deg. Recall that NG1 = 41.)

MU = μ = 0.10 = coefficient of friction of gear train (pivots and tooth-to-tooth contacts) and escape wheel pivot (constant for a computer run)

MU1 = μ_1 = 0.10 = coefficient of friction of pallet-escape wheel interface and pallet pivot (constant for a computer run)

LU = LL = L_U = L_L = 0.177 = distance from midplane to bearing plate half thickness

J1 = J_1 = 0.95 = initialization parameter for mesh no. 1. (The zero value corresponds to earliest possible contact of mesh (ref 2).)

J2 = J_2 = 0.95 = initialization parameter for mesh no. 2

Projectile Kinematics and Parameters

The projectile kinematics are programmed in subroutine AERO according to the expressions given in appendix E of reference 6 with the following parameters:

KP = K_p = 100

THETIN = 8 deg

TV = T_{var} = 2 deg

KN = K_n = 10

To express the kinematics of the aeroballistic system such that it conforms to the applicable S&A coordinate system, which may be located above or below the mechanism plane, appendix G introduces the signum function s_8 (eqs G-7 to G-12 and G-15).

Thus for the present case:

$$S8 = s_8 = -1$$

The drag deceleration is given by:

$$DDZ = s_8(\ddot{Z})$$

where $\ddot{Z} = 386.4 \times 10$. (The latter represents a deceleration of 10g, but is given as an absolute value.)

Depending on whether the mechanism is located on top or below the mechanism plane, the coordinates R_x, R_y, and R_z of the geometric center C of the mechanism plane with respect to the projectile center of mass O_{PR} must also be expressed with the help of the signum function s_8 (figs. C-1 and D-1).

Thus generally

$$R_{xgen} = R_x$$

$$R_{ygen} = s_8 R_y$$

$$R_{zgen} = s_8 R_z$$

The specific value used are:

$$RX = R_x = 0.001 \text{ in.}$$

$$RY = R_y = 0.001 \text{ in.}$$

$$RZ = R_z = 20.0 \text{ in.}$$

Output Data

The data blocks following the input data represent the results of various computations.

Fuze Geometry and Contact Angles of Both Meshes

The angles BETA1D = β_1 to BETA3D = β_3 and GAMMA2D = γ_2 to GAMMA4D = γ_4 are printed for checking purposes. In addition, the following earliest possible, transition and latest possible contact angles are given for both meshes (app F):

<u>Mesh No. 1</u>

PHI1TD = Transition angle of rotor no. 1

PHI2PTD = Transition angle of pinion no. 2

PHI1ID = Earliest possible contact angle of rotor no. 1

PH2PID = Earliest possible contact angle of pinion no. 2

PHI1FD = Latest possible contact angle of rotor no. 1

PH2PFD = Latest possible contact angle of pinion no. 2

<u>Mesh No. 2</u>

PHI2TD = Transition angle of gear no. 2

PHISTD = Transition angle of pinion no. 3 (escape wheel)

PHI2ID = Earliest possible contact angle of gear no. 2

PHISID = Earliest possible contact angle of pinion no. 3

PHI2FD = Latest possible contact angle of gear no. 2

PHISFD = Latest possible contact angle of pinion no. 3

Coupled Motion

The first coupled motion output refers to the entrance side of the verge. For each time T of the coupled motion, the following variables are computed:

PHI = ϕ = instantaneous escape wheel angle (deg)

PHIDOT = $\dot{\phi}$ = escape wheel angular velocity (rad/sec)

G = g = pallet - escape wheel contact position (in.) (ref 5, app C, eq C-15)

PSID = ψ = pallet angle (deg)

PSIDOT = $\dot{\psi}$ pallet angular velocity (rad/sec)

PHITOT = ϕ_T = cumulative escape wheel angle (deg)

F23 = F_{23} = normal contact force of gear no. 2 on pinion no. 3 (lb) for various mesh contact modes. The associated additional subscripts, such as RR, etc., are defined in table 1.

F12 = F_{12} = normal contact force of gear no. 1 on pinion no. 2 (lb), for various mesh contact modes (table 1).

PN = P_n = normal contact force between escape wheel and pallet (lb), computed according to equations D-969, D-992, D-1015, and D-1037, depending on specific contact mode, which can be determined from the subscript of the contact forces F_{12} and F_{23}.

PNPSI = P_n = normal contact force between escape wheel and pallet (lb), computed according to equation D-967 (app D) (serves for checking and requires the computations of ψ and $\dot{\psi}$).

DDPHI = $\ddot{\phi}$ = escape wheel angular acceleration (rad/sec^2), Runge-Kutta output

Free Motion

The first free motion on the exit side follows the coupled motion on the entrance side of the verge. For each time T of the free motion, the following variables are evaluated:

PHI = ϕ = instantaneous escape wheel angle (deg)

PHIDOT = $\dot{\phi}$ = escape wheel angular velocity (rad/sec)

PSI = ψ = pallet angle (deg)

PSIDOT = $\dot{\psi}$ = pallet angular velocity (rad/sec)

PHITOT = ϕ_T = cumulative escape wheel angle (deg)

T12 = T_{12} = normal contact force of gear no. 1 on pinion no. 2 for free motion (lb) (additional subscripts according to table 1)

T23 = T_{23} = normal contact force of gear no. 2 on escape wheel pinion for free motion (lb) (additional subscripts according to table 1)

F = f = contact sensing parameter (ref 5, app E)

GP = g' = second contact sensing parameter (ref 5, app E)

Impact

The first exit impact follows the first exit free motion. Just preceding the IMPACT label, the program prints the values of VP = V_{TNi} and VS = V_{SNi}, which stand for the pre-impact velocity components, normal to the verge face of both the pallet and escape wheel contact points (ref 5, app D, eq D-13). Subsequent to the IMPACT label, the referred moment of inertia ISTOT is computed for the applicable pre-impact mode according to equations D-1073 to D-1076, as applicable. After that, one finds the following variables:

PHI = ϕ = instantaneous escape wheel angle (deg), same as before impact

PHIDOT = $\dot{\phi}_f$ = post-impact escape wheel angular velocity (rad/sec) (app D, eq D-1071)

PSI = ψ = pallet angle (deg), same as before impact

PSIDOT = $\dot{\psi}_f$ = post-impact pallet angular velocity (rad/sec) (app D, eq D-1072)

PHITOT = ϕ_T = cumulative escape wheel angle (deg), same as before impact

VP = V_{TNf} = post-impact normal velocity component of pallet at contact point (ref 5, app D, eq D-15)

VS = V_{SNf} = post-impact normal velocity component of escape wheel tooth at contact point (ref 5, app D, eq D-13)

In the present program, the post-impact VP is equal to VS since the coefficient of restitution is zero.

Number of Turns-to-Arm and Maximum Contact Forces

The number of turns-to-arm at 30,000 rpm is obtained with the help of that time T_{1595} which corresponds to the escape wheel angle PHICUTD = 1595 deg. Thus, with T_{1595} = 0.09308 sec.

$$\text{number of turns-to-arm} = \frac{30000}{60} \times 0.09308 = 46.54 \text{ turns}$$

CONCLUSIONS

While it was not the purpose of this investigation to undertake a parametric study of the mechanism for which the program was written, the program was sufficiently tested to confirm that such a study is possible. It may include variations in masses and moments of inertia of all components; variations in the locations of the centers of mass of the verge and the rotor; variations of clock gear, escapement and fuze geometries as well as various friction and coefficient of restitution conditions. In addition, the aeroballistic data can also be varied. This makes it possible to determine the functioning limits of the mechanism under pathological projectile flight conditions.

The present work reports only on a single test run using the M577 fuze data with a system coefficient of friction of 0.1. This is assumed to be representative of actual test conditions since previous simulations of verge escapements showed that the range of actual experimental results (with spin only) may be reproduced with coefficients of friction between 0.1 and 0.2. A zero coefficient of restitution is used in the impact model (ref 4 and 5).

Previous high-speed motion picture observation of pin pallet escapements showed that the impacts were essentially inelastic and that therefore a zero coefficient restitution was justified.

The test run with a spin rate of 30,000 RPM also contained small precession and nutation velocities, chosen in the manner shown in appendix E.

Finally, it is to be noted that this work is the first where clock gear teeth were incorporated into the mathematical model of an S&A mechanism. To this end both forward and reverse kinematics of such gear trains had to be developed, as shown in appendix F.

REFERENCES

1. Lowen, G. G. and Tepper, F. R., "Fuze Gear Train Analysis," Technical Report ARLCD-TR-79030, ARRADCOM, Dover, NJ, December 1979.

2. Lowen, G. G. and Tepper, F. R., "Fuze Gear Train Efficiency," Technical Report ARLCD-TR-80024, ARRADCOM, Dover, NJ, November 1981.

3. Lowen, G. G. and Tepper, F. R., "Dynamics of the Pin Pallet Runaway Escapement," Technical Report ARLCD-TR-77062, ARRADCOM, Dover, NJ, June 1978.

4. Lowen, G. G. and Tepper, F. R., "Computer Simulations of Artillery S&A Mechanisms (Involute Gear Train and Pin Pallet Runaway Escapement)," Technical Report ARLCD-TR-81039, ARRADCOM, Dover, NJ, July 1982.

5. Lowen, G. G. and Tepper, F. R., "Computer Simulation of Artillery S&A Mechanisms (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-82013, ARRADCOM, Dover, NJ, November 1982.

6. Tepper, F. R. and Lowen, G. G., "Computer Simulation of Artillery Safing and Arming Mechanism in Aeroballistic Environment (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-83050, Dover, NJ, July 1984.

7. Lowen, G. G., "Development of Simulation Techniques for the M739 and M577 Fuzes," Contractor Report ARLCD-CR-84003, ARDC, Dover, NJ, April 1984.

8. Hartenberg, R. and Denavit, J., Kinematic Synthesis of Linkages, McGraw-Hill Book Co., New York, NY, 1964.

9. Goldstein, H., Classical Mechanics, Addison-Wesley Publishing Co., Inc., Reading, MA, 1959.

10. Shames, I. H., Engineering Mechanics, Statics, and Dynamics, third edition, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1980.

APPENDIX A

KINEMATICS OF AEROBALLISTIC SYSTEMS

ANGULAR VELOCITIES AND ACCELERATIONS IN TERMS OF PROJECTILE-FIXED COORDINATES

A projectile which experiences general aeroballistic motion, i.e., spin about an axis through its center of mass as well as precession and nutation of this spin axis, is shown in figure A-1. (Point O_{PR} represents the origin of the coordinate system in this figure and the spin axis coincides with the geometric one.)

The spin angle, spin velocity, and spin acceleration are expressed by the time dependent quantities ϕ_E, $\dot{\phi}_E$, and $\ddot{\phi}_E$. (The subscript E stands for the Euler angles, which are involved in this derivation.) Similarly, the kinematic quantities associated with the precession are ψ_E, $\dot{\psi}_E$, and $\ddot{\psi}_E$. The nutation variables are θ_E, $\dot{\theta}_E$, and $\ddot{\theta}_E$ (refs 1 and 2).

With spin, precession, and nutation angular velocity vectors, together with their associated angles (fig. A-1), orthogonal angular velocity components in terms of the projectile fixed x-y-z system may be obtained as follows:

Let

$$\bar{\omega}_{b/a} = \omega_x \bar{i} + \omega_y \bar{j} + \omega_z \bar{k} \tag{A-1}$$

where $\bar{\omega}_{b/a}$ represents the angular velocity of the projectile b with respect to the inertial frame a. Then

$$\omega_x = \dot{\theta}_E \cos \phi_E + \dot{\psi}_E \sin \theta_E \sin \phi_E \tag{A-2}$$

$$\omega_y = -\dot{\theta}_E \sin \phi_E + \dot{\psi}_E \sin \theta_E \cos \phi_E \tag{A-3}$$

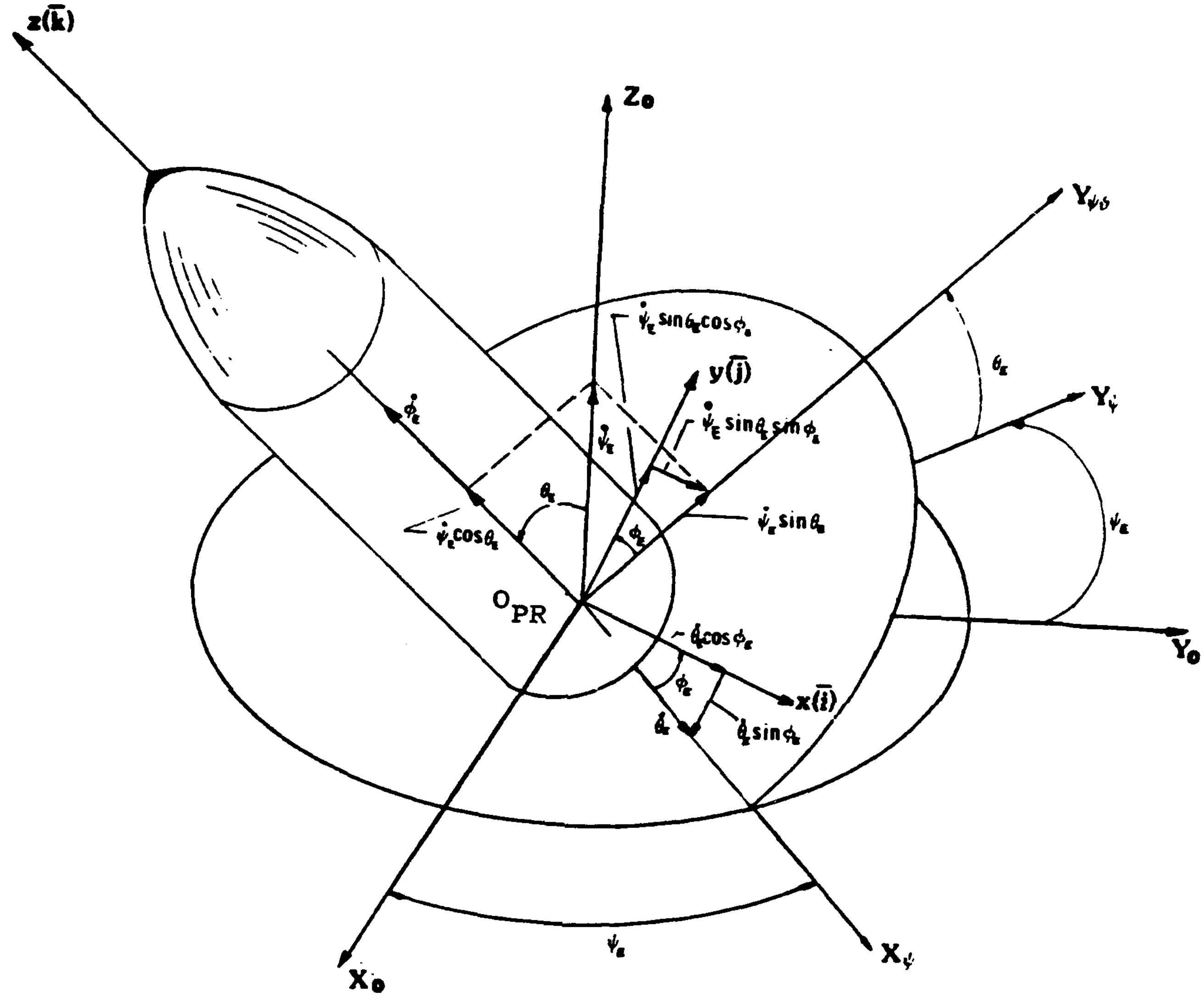
$$\omega_z = \dot{\phi}_E + \dot{\psi}_E \cos \theta_E \tag{A-4}$$

The absolute angular acceleration of the projectile, i.e.

$$\dot{\bar{\omega}}_{b/a} = \dot{\omega}_x \bar{i} + \dot{\omega}_y \bar{j} + \dot{\omega}_z \bar{k} \tag{A-5}$$

is obtained by differentiation of the body fixed quantities with respect to time. Thus

$$\dot{\omega}_x = \ddot{\theta}_E \cos \phi_E - \dot{\theta}_E \dot{\phi}_E \sin \phi_E + \ddot{\psi}_E \sin \theta_E \sin \phi_E$$
$$+ \dot{\psi}_E \dot{\theta}_E \cos \theta_E \sin \phi_E + \dot{\psi}_E \dot{\phi}_E \sin \theta_E \cos \phi_E \tag{A-6}$$



Note: This system is later described with capital letters X-Y-Z

Figure A-1. Projectile fixed x-y-z system

$$\dot{\omega}_y = -\ddot{\theta}_E \sin\phi_E - \dot{\theta}_E\dot{\phi}_E \cos\phi_E + \ddot{\psi}_E \sin\theta_E \cos\phi_E$$

$$+ \dot{\psi}_E\dot{\theta}_E \cos\theta_E \cos\phi_E - \dot{\psi}_E\dot{\phi}_E \sin\theta_E \sin\phi_E \qquad \text{(A-7)}$$

$$\dot{\omega}_z = \ddot{\phi}_E + \ddot{\psi}_E \cos\theta_E - \dot{\psi}_E\dot{\theta}_E \sin\theta_E \qquad \text{(A-8)}$$

Pallet-Fixed Coordinates

The relationship of the pallet-fixed ξ_p - η_p - ζ_p system with respect to the projectile fixed X-Y-Z and x′-y′-z′ systems is shown in figure A-2 (ref 1).

The ξ_p - η_p plane is parallel to the x′-y′ and X-Y planes and contains the pallet center of mass C_p. The ζ_p-axis is parallel to the z and z′ axes.

The pallet angles ψ and ψ_c are measured in the ξ_p - η_p plane and are otherwise defined as in reference 1. Before determining the absolute angular velocity and acceleration of the pallet, a number of unit vectors should be defined. According to equations B-28 and B-29 of ref 2

$$\bar{i}' = -\cos\beta_3\bar{i} - \sin\beta_3\bar{j} \qquad \text{(A-9)}$$

and

$$\bar{j}' = \sin\beta_3\bar{i} - \cos\beta_3\bar{j} \qquad \text{(A-10)}$$

Further, when expressed in the primed system, pallet fixed unit vectors become

$$\bar{n}_{\xi_p} = \cos\beta\bar{i}' + \sin\beta\bar{j}' \qquad \text{(A-11)}$$

$$\bar{n}_{\eta_p} = -\sin\beta\bar{i}' + \cos\beta\bar{j}' \qquad \text{(A-12)}$$

where

$$\beta = \psi + \psi_c \qquad \text{(A-13)}$$

If equations A-9 and A-10 are substituted into the above expressions, after some trigonometric simplifications, the following expressions are obtained for the pallet fixed unit vectors in terms of the X-Y-Z system

$$\bar{n}_{\xi_p} = -\cos\alpha'\bar{i} - \sin\alpha'\bar{j} \qquad \text{(A-14)}$$

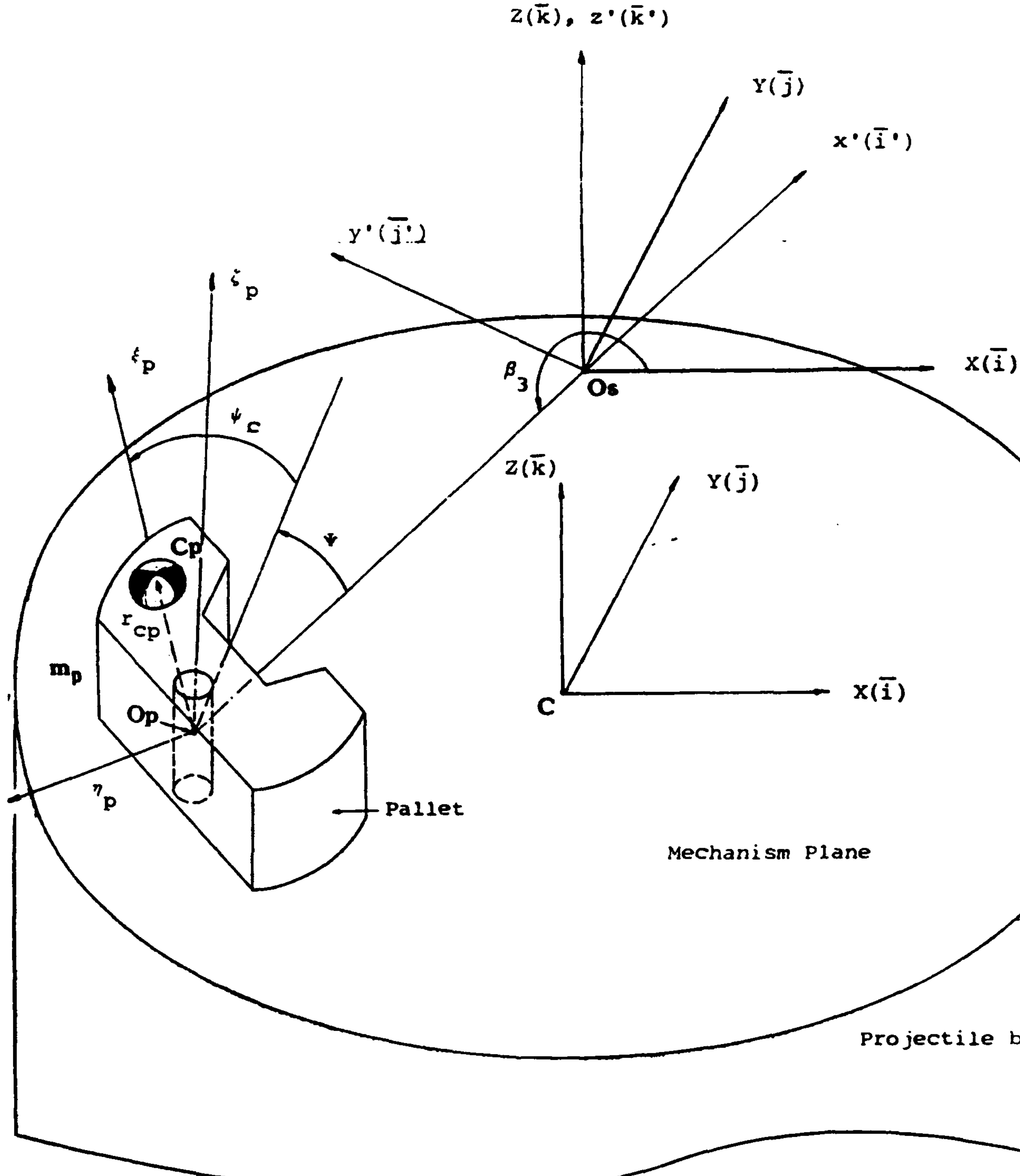


Figure A-2. Pallet-fixed ξ_p-η_p-ζ_p coordinate system

and

$$\bar{n}_{\eta_p} = \sin\alpha'\bar{i} - \cos\alpha'\bar{j} \tag{A-15}$$

where

$$\alpha' = \psi + \psi_c + \beta_3 \tag{A-16}$$

Because of the given parallel axes

$$\bar{n}_{\zeta_p} = \bar{k}' = \bar{k} \tag{A-17}$$

If the relative angular velocity of the pallet P with respect to the projectile b is given by

$$\bar{\omega}_{p/b} = \dot{\psi}\,\bar{n}_{\zeta_p} \tag{A-18}$$

then its absolute angular velocity $\bar{\omega}_{p/a}$ is given by

$$\bar{\omega}_{p/a} = \bar{\omega}_{p/b} + \bar{\omega}_{b/a} \tag{A-19}$$

To express equation A-16 in pallet-fixed terms, it is necessary to transform equation A-1 which gave $\bar{\omega}_{b/a}$. According to equations A-14 and A-15

$$\bar{i} = -\cos\alpha'\,\bar{n}_{\xi_p} + \sin\alpha'\,\bar{n}_{\eta_p} \tag{A-20}$$

and

$$\bar{j} = -\sin\alpha'\,\bar{n}_{\xi_p} - \cos\alpha'\,\bar{n}_{\eta_p} \tag{A-21}$$

Thus, one obtains in the pallet fixed system

$$\bar{\omega}_{b/a} = -\left[\omega_x\cos\alpha' + \omega_y\sin\alpha'\right]\bar{n}_{\xi_p} + \left[\omega_x\sin\alpha' - \omega_y\cos\alpha'\right]\bar{n}_{\eta_p} + \omega_z\,\bar{n}_{\zeta_p} \tag{A-22}$$

Finally, the absolute angular velocity of the pallet $\bar{\omega}_{p/a}$ becomes with equations A-18 and A-19

$$\bar{\omega}_{p/a} = \omega_{\xi_p}\,\bar{n}_{\xi_p} + \omega_{\eta_p}\,\bar{n}_{\eta_p} + \omega_{\zeta_p}\,\bar{n}_{\zeta_p} \tag{A-23}$$

where

$$\omega_{\xi_p} = -(\omega_x \cos\alpha' + \omega_y \sin\alpha') \qquad \text{(A-24)}$$

$$\omega_{\eta_p} = \omega_x \sin\alpha' - \omega_y \cos\alpha' \qquad \text{(A-25)}$$

$$\omega_{\zeta_p} = \omega_z + \dot{\psi} \qquad \text{(A-26)}$$

The absolute angular acceleration $\bar{\dot{\omega}}_{p/a}$ of the pallet is obtained by the differentiation with respect to time of the measure numbers of equation A-23, i.e.,

$$\bar{\dot{\omega}}_{p/a} = \dot{\omega}_{\xi_p} \bar{n}_{\xi_p} + \dot{\omega}_{\eta_p} \bar{n}_{\eta_p} + \dot{\omega}_{\zeta_p} \bar{n}_{\zeta_p} \qquad \text{(A-27)}$$

where

$$\dot{\omega}_{\xi_p} = -\left(\dot{\omega}_x \cos\alpha' - \omega_x \dot{\psi} \sin\alpha' + \dot{\omega}_y \sin\alpha' + \omega_y \dot{\psi} \cos\alpha'\right) \qquad \text{(A-28)}$$

$$\dot{\omega}_{\eta_p} = \dot{\omega}_x \sin\alpha' + \omega_x \dot{\psi} \cos\alpha' - \dot{\omega}_y \cos\alpha' + \omega_y \dot{\psi} \sin\alpha' \qquad \text{(A-29)}$$

$$\dot{\omega}_{\zeta_p} = \dot{\omega}_z + \ddot{\psi} \qquad \text{(A-30)}$$

Rotor-Fixed Coordinates

The relationship between the rotor-fixed $\xi_1 - \eta_1 - \zeta_1$ system and the projectile fixed X-Y-Z system is shown in figure A-3 (see also ref 1). The $\xi_1 - \eta_1$ plane is parallel to the X-Y plane and contains the center of mass C_1 of the rotor (referred to as link 1 below). The ξ_1-axis connects the point O_1 on the rotor pivot centerline and point C_1.

The rotor angles ϕ_{1RC} and ϕ_{1R} are measured in the $\xi_1 - \eta_1$ plane. ϕ_{1RC} represents the initial position of the ξ_1-axis, i.e. the ξ_{1o} axis, with respect to the x-axis.

The unit vector associated with the rotor-fixed system are given by

$$\bar{n}_{\xi_1} = \cos(\phi_{1RC} + \phi_{1R})\bar{i} + \sin(\phi_{1RC} + \phi_{1R})\bar{j} \qquad \text{(A-31)}$$

$$\bar{n}_{\eta_1} = -\sin(\phi_{1RC} + \phi_{1R})\bar{i} + \cos(\phi_{1RC} + \phi_{1R})\bar{j} \qquad \text{(A-32)}$$

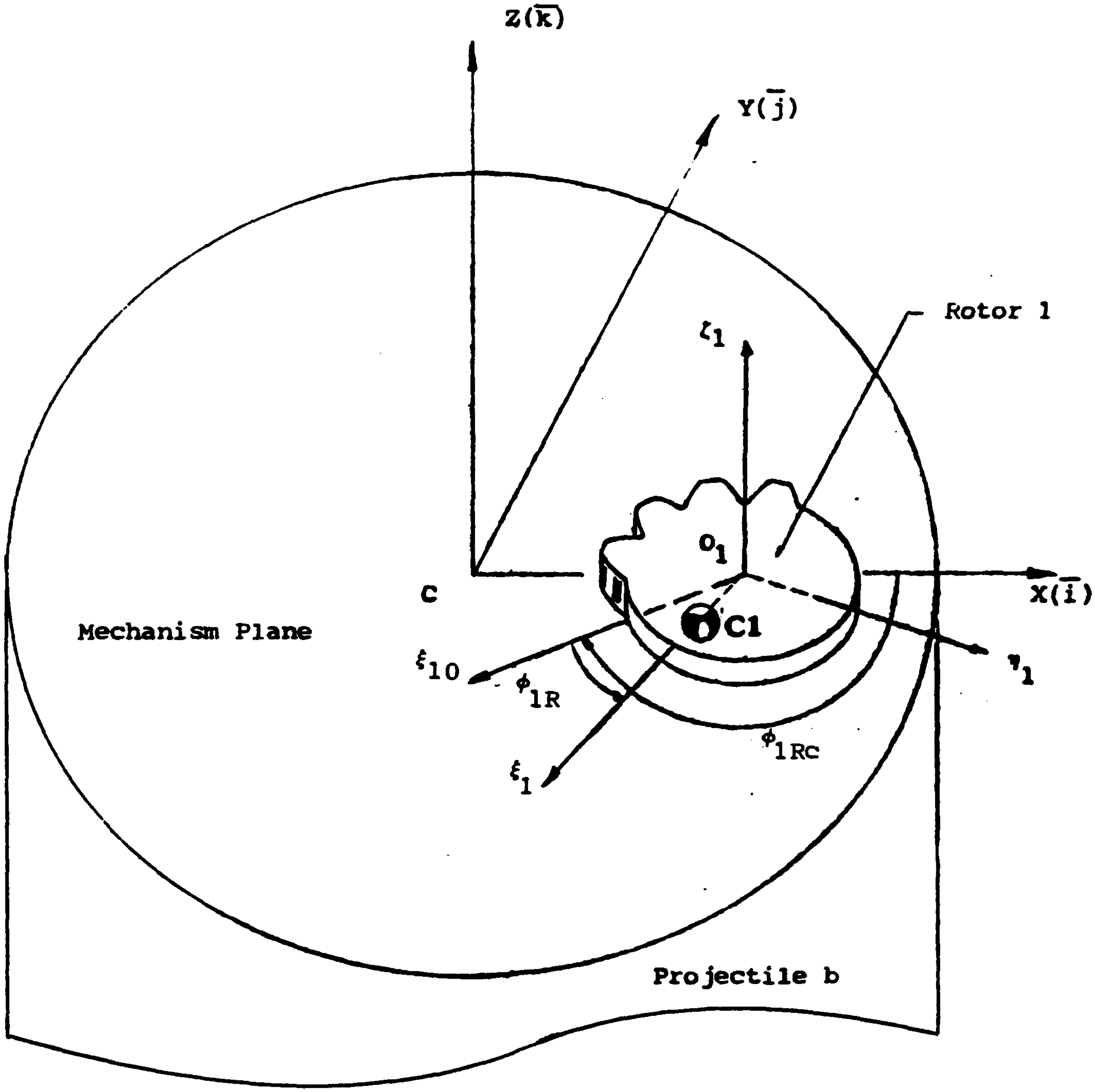


Figure A-3. Rotor-fixed ξ_1-η_1-ζ_1 coordinate system

and

$$\bar{n}_{\zeta_1} = \bar{k} \tag{A-33}$$

The effect of the gear train on the relationship between the angle ϕ_{1R} and the total escape wheel angle ϕ_T will presently be neglected. It is more complicated for clock gearing than for involute gearing (see ref 2, eq B123), and will be discussed in detail in Appendix F. Then with

$$\gamma = \phi_{1RC} + \phi_{1R} \tag{A-34}$$

The absolute angular velocity $\bar{\omega}_{b/a}$ of the projectile is expressed in terms of the rotor fixed coordinates with the help of equations A-1 and A-31 to A-33

$$\bar{\omega}_{b/a} = \omega_x \bar{i} + \omega_y \bar{j} + \omega_z \bar{k}$$

$$= \omega_x (\cos\gamma\, \bar{n}_{\xi_1} - \sin\gamma\, \bar{n}_{\eta_1}) + \omega_y (\sin\gamma\, \bar{n}_{\xi_1} + \cos\gamma\, \bar{n}_{\eta_1}) + \omega_z \bar{n}_{\zeta_1}$$

or

$$\bar{\omega}_{b/a} = [\omega_x \cos\gamma + \omega_y \sin\gamma]\, \bar{n}_{\xi_1} + [-\omega_x \sin\gamma + \omega_y \cos\gamma]\, \bar{n}_{\eta_1} + \omega_z \bar{n}_{\zeta_1} \tag{A-35}$$

To obtain the total angular velocity $\bar{\omega}_{1/a}$ of the rotor, its relative angular velocity $\bar{\omega}_{1/a} = \dot{\bar{\phi}}_1$ must be added vectorially to equation A-35

$$\bar{\omega}_{1/a} = \bar{\omega}_{b/a} + \dot{\phi}_1 \bar{n}_{\zeta_1} \tag{A-36}$$

Then, with equation A-33

$$\bar{\omega}_{1/a} = \omega_{\xi_1} \bar{n}_{\xi_1} + \omega_{\eta_1} \bar{n}_{\eta_1} + \omega_{\zeta_1} \bar{n}_{\zeta_1} \tag{A-37}$$

where

$$\omega_{\xi_1} = \omega_x \cos\gamma + \omega_y \sin\gamma \tag{A-38}$$

$$\omega_{\eta_1} = -\omega_x \sin\gamma + \omega_y \cos\gamma \tag{A-39}$$

$$\omega_{\zeta_1} = \omega_z + \dot{\phi}_1 \tag{A-40}$$

To obtain the absolute angular acceleration $\dot{\bar{\omega}}_{1/a}$ of the rotor, differentiate the measure numbers of equation A-37 with respect to time. *Therefore,*

$$\dot{\bar{\omega}}_{1/a} = \dot{\omega}_{\xi_1} \bar{n}_{\xi_1} + \dot{\omega}_{\eta_1} \bar{n}_{\eta_1} + \dot{\omega}_{\zeta_1} \bar{n}_{\zeta_1} \tag{A-41}$$

where

$$\dot{\omega}_{\xi_1} = \dot{\omega}_x \cos\gamma - \omega_x \dot{\phi}_1 \sin\gamma + \dot{\omega}_y \sin\gamma + \omega_y \dot{\phi}_1 \cos\gamma \tag{A-42}$$

$$\dot{\omega}_{\eta_1} = - \dot{\omega}_x \sin\gamma - \omega_x \dot{\phi}_1 \cos\gamma + \dot{\omega}_y \cos\gamma - \omega_y \dot{\phi}_1 \sin\gamma \tag{A-43}$$

$$\dot{\omega}_{\zeta_1} = \dot{\omega}_z + \ddot{\phi}_1 \tag{A-44}$$

TWO EQUIVALENT METHODS FOR OBTAINING EXPRESSIONS FOR ABSOLUTE ANGULAR VELOCITIES AND ACCELERATIONS OF COMPONENTS, SUCH AS THE PALLET, IN TERMS OF PROJECTILE-FIXED COORDINATES

An an example, ref 1 on pages 31-33 shows two equivalent methods for obtaining the absolute angular velocity and acceleration of the pallet in terms of the projectile-fixed x′-y′z′ system.

The first of these consists simply of the substitution of the unit vectors of eqs A-11 to A-13 into expressions A-23 and A-27, respectively.

The second method, which produces the identical results, interprets the relative angular velocity vector as a variable vector in the primed system. The absolute angular velocity of the pallet is obtained from

$$\bar{\omega}_{p/a_{x'y'z'}} = \dot{\psi}\bar{k}' + \bar{\omega}_{b/a_{x'y'z'}} \tag{A-45}$$

The absolute angular acceleration results from the application of the appropriate carrier-fixed rule of differentiation

$$\dot{\bar{\omega}}_{p/a_{x'y'z'}} = \ddot{\psi}\bar{k}' + \bar{\omega}_{b/a_{x'y'z'}} \times \dot{\psi}\bar{k}' + \dot{\bar{\omega}}_{b/a_{x'y'z'}} \tag{A-46}$$

(See also eq B-9 in appendix B.)

REFERENCES

1. Tepper, F. R. and Lowen, G. G., "Computer Simulation of Artillery Safing and Arming Mechanism in Aeroballistic Environment (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-83050, ARDC, Dover, NJ, July 1984.

2. Lowen, G. G. and Tepper, F. R., "Computer Simulation of Artillery S&A Mechanisms (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-82013, ARRADCOM, Dover, NJ, November 1982.

APPENDIX B

ANGULAR MOMENTUM AND ITS DERIVATIVES IN VARIOUS COORDINATE SYSTEMS

ANGULAR MOMENTUM EXPRESSION

The angular momentum vector $\overline{H}_0$, with respect to a point 0, has the general expression

$$\overline{H}_0 = [I_{xx}\omega_x - I_{xy}\omega_y - I_{zx}\omega_z]\overline{i} + [-I_{xy}\omega_x + I_{yy}\omega_y - I_{yz}\omega_z]\overline{j}$$

$$+ [-I_{zx}\omega_x - I_{yz}\omega_y + I_{zz}\omega_z]\overline{k} \tag{B-1}$$

The above holds for all types of body-fixed and space-fixed coordinate systems. If principal axes are involved, the products of inertia vanish. Note that the angular velocity component must be absolute.

Derivative of Body-Fixed Angular Momentum Vector: Torque Equation

Body b in general motion is shown in figure B-1. It contains the body fixed X-Y-Z system and its angular momentum may be expressed with the help of equation B-1.

The time derivative of the angular momentum with respect to the inertial X_o - Y_o - Z_0 system is obtained from

$$\dot{\overline{H}}_{0/X_oY_oZ_o} = \frac{d}{dt}(\overline{H}_0)_{XYZ} + \overline{\omega} \times \overline{H}_0 \tag{B-2}$$

where

$$\frac{d}{dt}(\overline{H}_0)_{XYZ} = \text{derivative of the measure numbers in equation B-1 and}$$

$$\overline{\omega} \times \overline{H}_0 = (\omega_x\overline{i} + \omega_y\overline{j} + \omega_z\overline{k}) \times \overline{H}_0$$

It is to be recalled at this point, that the absolute angular acceleration of body b is given by

$$\dot{\overline{\omega}} = \dot{\omega}_x\overline{i} + \dot{\omega}_y\overline{j} + \dot{\omega}_z\overline{k} \tag{B-3}$$

Both $\overline{\omega}$ and $\dot{\overline{\omega}}$ are now expressed in terms of the body fixed coordinates.

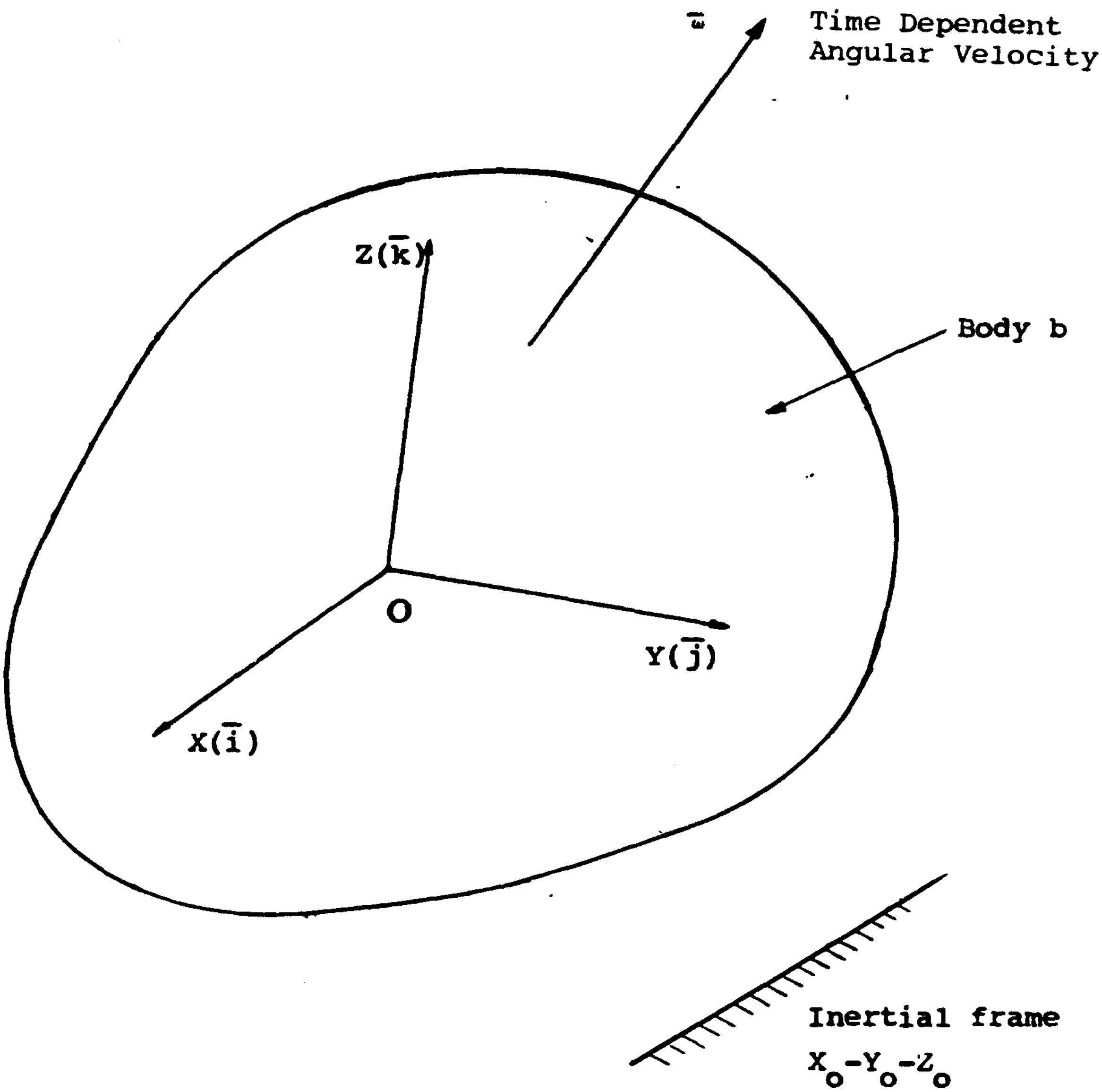


Figure B-1. Body b containes X-Y-Z system

Upon performing all operations of equation B-2, the torque equation with respect to point 0 results

$$\overline{M}_0 = \dot{\overline{H}}_{0/X_oY_oZ_o} = [I_{xx}\dot{\omega}_x + \omega_y\omega_z(I_{zz} - I_{yy}) + I_{xy}(\omega_z\omega_x - \dot{\omega}_y)$$

$$- I_{zx}(\dot{\omega}_z + \omega_x\omega_y) - I_{yz}(\omega_y^{\ 2} - \omega_z^{\ 2})]\overline{i}$$

$$+ [I_{yy}\dot{\omega}_y + \omega_x\omega_z(I_{xx} - I_{zz}) + I_{yz}\left(\omega_x\omega_y - \dot{\omega}_z\right)$$

$$- I_{xy}(\dot{\omega}_x + \omega_y\omega_z) - I_{zx}\left(\omega_z^2 - \omega_x^2\right)]\,\overline{j}$$

$$+ [I_{zz}\dot{\omega}_z + \omega_x\omega_y(I_{yy} - I_{xx}) + I_{zx}\left(\omega_y\omega_z - \dot{\omega}_x\right)$$

$$- I_{yz}(\dot{\omega}_y + \omega_x\omega_z) - I_{xy}(\omega_x^{\ 2} - \omega_y^{\ 2})]\overline{k} \qquad \text{(B-4)}$$

When $I_{xy} = I_{yz} = I_{zx} = 0$, the above expression becomes the well known Euler torque equation.

Derivative of an Angular Momentum Vector Which is Described in Terms of the Body-Fixed System of a Carrier: Torque Equation

The carrier body b which has general rotational motion is shown in figure B-2. Its absolute angular velocity and acceleration are given in terms of the indicated body-fixed system, i.e.

$$\overline{\omega}_{b/a} = \omega_{b/ax}\overline{i} + \omega_{b/ay}\overline{j} + \omega_{b/az}\overline{k} \qquad \text{(B-5)}$$

and

$$\dot{\overline{\omega}}_{b/a} = \dot{\omega}_{b/ax}\overline{i} + \dot{\omega}_{b/ay}\overline{j} + \dot{\omega}_{b/az}\overline{k} \qquad \text{(B-6)}$$

respectively.

The symmetrical body c rotates about an axis parallel to the Z-axis with respect to body b with the relative angular velocity

$$\overline{\omega}_{c/b} = \omega_{c/b}(t)\overline{k} \qquad \text{(B-7)}$$

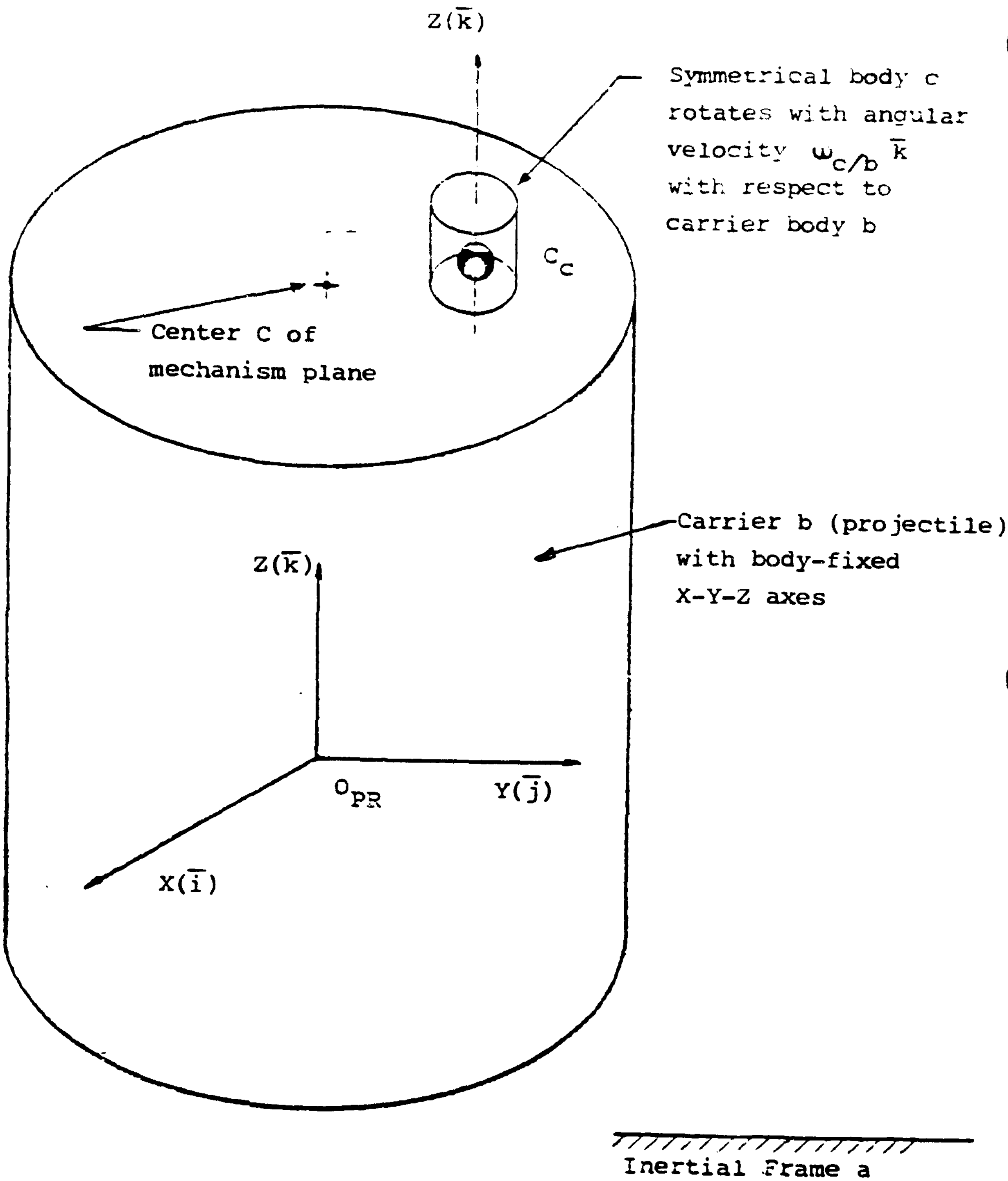


Figure B-2. Symmetrical body c has relative rotation about Z-axis with respect to carrier b

If the absolute angular velocity vector $\bar{\omega}_{c/a}$ off this body c is expressed in terms of the carrier-fixed X-Y-Z system, the following results

$$\bar{\omega}_{c/a} = \bar{\omega}_{c/b} + \bar{\omega}_{b/a} \tag{B-8}$$

(For comparison see equation A-45.)

To obtain the absolute angular velocity $\dot{\bar{\omega}}_{c/a}$ in terms of the projectile-fixed system, interpret $\omega_{c/b}$ as a variable vector in the X-Y-Z system. Then,

$$\dot{\bar{\omega}}_{c/a_{X_oY_oZ_o}} = \dot{\bar{\omega}}_{c/b} + \bar{\omega}_{b/a} \times \bar{\omega}_{c/b} + \dot{\bar{\omega}}_{b/a} \tag{B-9}$$

where

$\dot{\bar{\omega}}_{c/a} = \dot{\omega}_{c/b}\bar{k}$, the relative angular acceleration of component C with respect to projectile b

$\dot{\bar{\omega}}_{b/a}$ = given by equation B-6

Because body c is symmetrical, its products of inertia with respect to its center of mass C_c are zero. This symmetry also makes it possible to express its angular momentum with respect to point C_c in terms of the body-fixed system of the carrier b. (Regardless of the angle of body c with respect to body b, the moments of inertia I_{xx} and I_{yy}, expressed in terms of body b, remain invariant.) The angular momentum vector, with respect to point C_c, appropriately reduced, becomes according to equations B-1 and B-8

$$\bar{H}_{C_C} = I_{xx}\omega_{b/ax}\bar{i} + I_{yy}\omega_{b/ay}\bar{j} + I_{zz}\left(\omega_{b/az} + \omega_{c/b}\right)\bar{k} \tag{B-10}$$

The vector $\bar{H}_{C_c}$ must be interpreted as a variable vector in the carrier-fixed coordinate system. Its time derivative with respect to the initial system is therefore obtained by the following operations

$$\dot{\bar{H}}_{C_{c/X_oY_oX_o}} = \frac{d}{dt}(\bar{H}_{C_c})_{XYZ} + \bar{\omega}_{b/a} \times \bar{H}_{C_c} \tag{B-11}$$

When applied to equation B-10, the following is obtained

$$\dot{\overline{H}}_{C_{c/X_oY_oZ_o}} = I_{xx}\,\dot{\omega}_{b/ax}\,\overline{i} + I_{yy}\,\dot{\omega}_{b/ay}\,\overline{j} + I_{zz}\,(\dot{\omega}_{b/az} + \dot{\omega}_{c/b})\,\overline{k}$$

$$+ (\omega_{b/ax}\overline{i} + \omega_{b/ay}\overline{j} + \omega_{b/az}\overline{k}) \times [I_{xx}\omega_{b/ax}\overline{i} + I_{yy}\omega_{b/ay}\overline{j}$$

$$+ I_{zz}(\omega_{b/az} + \omega_{c/b})\overline{k}] \qquad \text{(B-12)}$$

The above becomes the torque equation with respect to point C_c

$$\dot{\overline{H}}_{C_{c/X_oY_oZ_o}} = \overline{M}_{C_c} = [I_{xx}\dot{\omega}_{b/ax} + I_{zz}\omega_{b/ay}(\omega_{b/az} + \omega_{c/b}) - I_{yy}\omega_{b/ay}\omega_{b/az}]\overline{i}$$

$$+ [I_{yy}\dot{\omega}_{b/ay} + I_{xx}\omega_{b/ax}\omega_{b/az} - I_{zz}\omega_{b/ax}(\omega_{b/az} + \omega_{c/b})]\overline{j}$$

$$+ I_{zz}(\dot{\omega}_{b/az} + \dot{\omega}_{c/b})\overline{k} \qquad \text{(B-13)}$$

APPENDIX C

ABSOLUTE ACCELERATION OF GEOMETRIC CENTER C OF THE S&A PLANE

The relationship between the center of mass C_{PR} of the projectile and the center C of the plane, where the S&A mechanism is located[1], is shown in figure C-1. The origin O_{PR} of the projectile-fixed X_P-Y_P-Z_P coordinate system lies on the geometric axis of the projectile. (The subscript P is now introduced in order to distinguish this system from the parallel X-Y-Z one, which is fixed both to the mechanism plane and the projectile.)

The geometric axis is assumed to be parallel to the spin axis of the projectile. The center of mass of the projectile, about which all rotation takes place, lies in the X_P-Y_P plane. Note that the figure shows the S&A mechanism to be in configuration 2, as seen from the tip of the projectile. The position vector from the center of mass to point C is given by

$$\bar{R} = R_x\bar{i} + R_y\bar{j} + R_z\bar{k} \tag{C-1}$$

It is assumed that the deceleration of the center of mass due to drag is only in the Z-direction and that it is given by

$$\bar{A}_{C_{PR}/\text{ground}} = \ddot{Z}\bar{k} \tag{C-2}$$

The absolute acceleration $\bar{A}_{C/\text{ground}}$ of point C, may then be obtained from

$$\bar{A}_{C/\text{ground}} = \bar{A}_{C_{PR}/\text{ground}} + \bar{\omega} \times (\bar{\omega} \times \bar{R}) + \dot{\bar{\omega}} \times \bar{R} \tag{C-3}$$

where $\bar{\omega}$ and $\dot{\bar{\omega}}$ are obtained from equations A-1 and A-5, respectively. (For clarity they were designated as $\bar{\omega}_{b/a}$ and $\dot{\bar{\omega}}_{b/a}$ in appendix A.)

When the operations of equation C-3 are carried out and equation C-2 is substituted, the following is obtained

$$\bar{A}_{C/\text{ground}} = G_x\bar{i} + G_y\bar{j} + G_z\bar{k} \tag{C-4}$$

where

$$G_x = (\omega_y R_y + \omega_z R_z)\omega_x - (\omega_y^2 + \omega_z^2)R_x + (\dot{\omega}_y R_z - \dot{\omega}_z R_y) \tag{C-5}$$

$$G_y = (\omega_x R_x + \omega_z R_z)\ \omega_y - (\omega_x^2 + \omega_z^2) R_y + (\dot{\omega}_z R_x - \dot{\omega}_x R_z) \tag{C-6}$$

$$G_z = (\omega_x R_x + \omega_y R_y)\omega_z - (\omega_x^2 + \omega_y^2) R_z + (\dot{\omega}_x R_y - \dot{\omega}_y R_x) + \ddot{Z} \tag{C-7}$$

[1]Note that in figure C-1 the S&A mechanism is located on the topside of the mechanism plane.

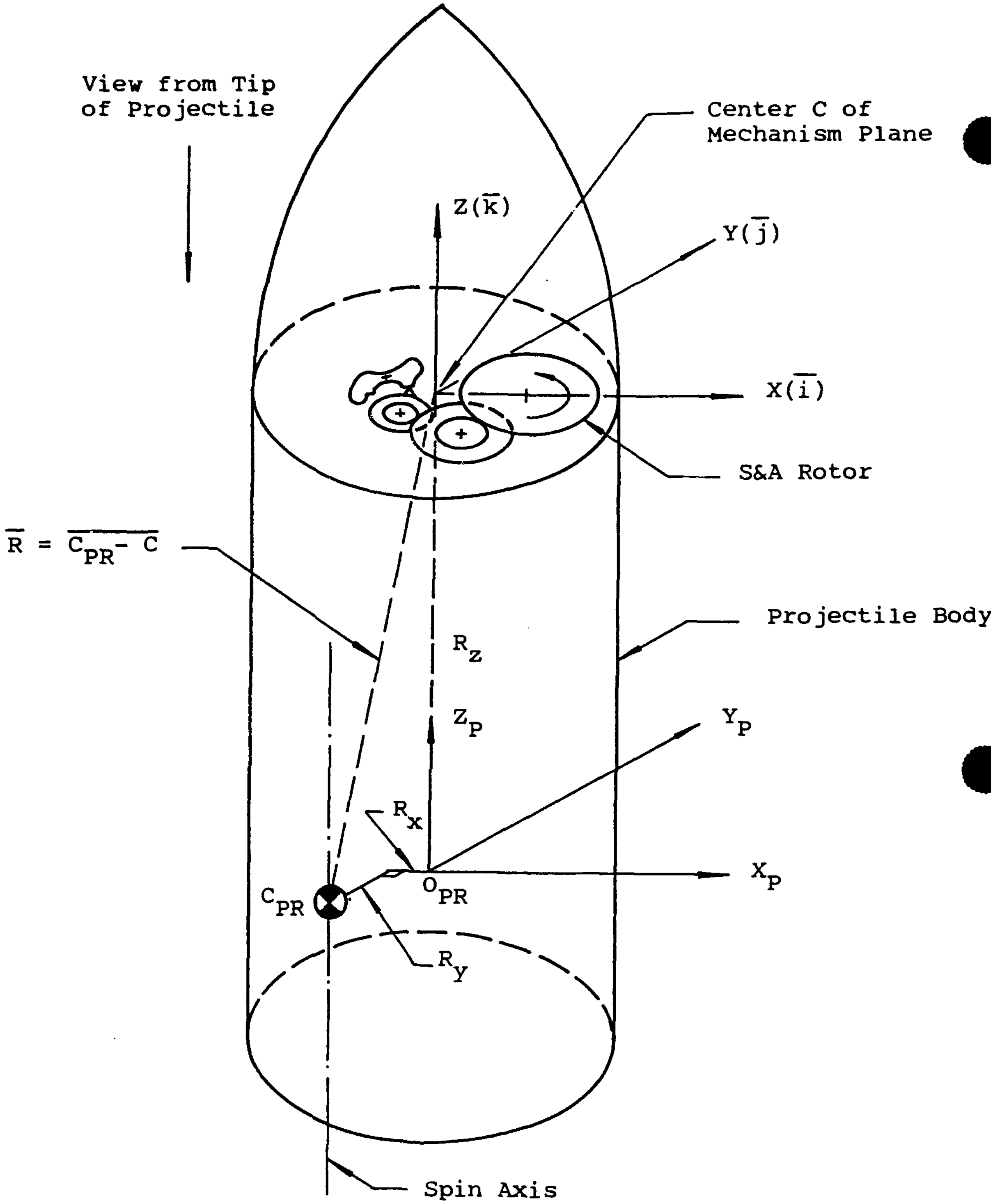


Figure C-1. *Relationship between center of mass C_{PR} of projectile and center C of mechanism plane. S&A is in configuration 2 as seen from the tip of the projectile. (S&A is located on upper side of the mechanism plane).*

APPENDIX D

DYNAMICS OF ROTOR-DRIVEN S&A MECHANISM WITH A TWO-PASS CLOCK GEAR TRAIN AND A VERGE RUNAWAY ESCAPEMENT OPERATING IN AN AEROBALLISTIC ENVIRONMENT

FUZE BODY CONFIGURATIONS AND THEIR RELATIONSHIPS TO PROJECTILE GEOMETRY

All the following expressions of the present simulation are directly applicable to the two fuze body configurations of references 1 and 2, as long as the involved S&A mechanisms appear in these configurations, with the rotor turning counterclockwise (ccw), when seen from the tip of the projectile toward its bottom (fig. C-1).

The S&A mechanism of the M577 fuze is located in its projectile so that its configuration 2, with the rotor turning ccw, becomes discernible only when an observer looks at it from the bottom of the projectile towards its tip.[1] As shown in figure D-1, this construction places the Y_P and Z_P axes of the projectile-fixed system, which is used to express the kinematics of the projectile, in opposite directions to the corresponding axes of the mechanism plane-fixed X-Y-Z system.

To be able to apply all the following simulation expressions to this situation, i.e., to be able to work in the mechanism plane system as shown in appendix G, it is necessary to reverse the signs of the Y and Z component values of the projectile angular velocity (eq. A-1) and angular acceleration (eq. A-5). Similarly, the signs of the Y and Z components of vector R (eq. C-1) and of the drag deceleration (eq. C-2) must be reversed.

All work concerning fuze body angles, as given in reference 3, is applicable regardless of the position of the S&A in the projectile as long as the fuze body has configuration 1 or 2.

DYNAMICS OF ESCAPEMENT IN COUPLED MOTION

Absolute Acceleration of Pallet Pivot O_p

The position of the pallet pivot O_p with respect to the geometric center C of the mechanism plane is shown in figure D-2. In addition, the relationship of the projectile-fixed x'-y'-z' system to the mechanism plane-fixed X-Y-Z system is indicated.

[1]In figure D-1 the S&A mechanism is located on the underside of the mechanism plane.

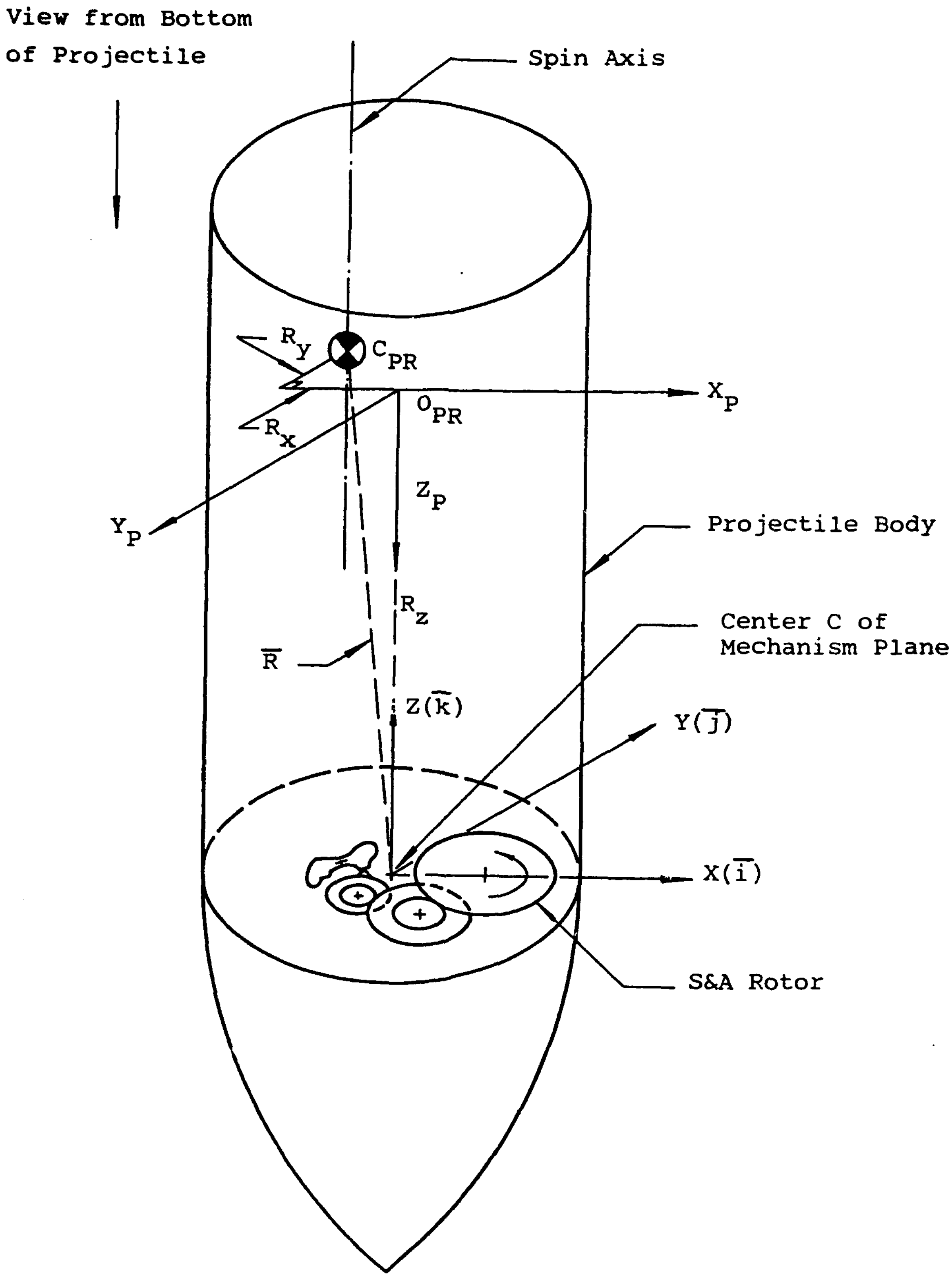


Figure D-1. Relationship between X_p-Y_p-Z_p system and mechanism plane fixed X-Y-Z system in M577 S&A. Configuration 2 is seen from bottom of projectile. (S&A is located on the underside of the mechanism plane.)

The absolute acceleration of point O_p is given by

$$\overline{A}_{O_p/ground} = \overline{A}_{O_p/C} + \overline{A}_{C/ground} \qquad \text{(D-1)}$$

where, $\overline{A}_{C/ground}$ is given by equation C-4 of appendix C and

$$\overline{A}_{O_p/C} = \overline{\omega} \times (\overline{\omega} \times \overline{\Re}_4) + \overline{\dot{\omega}} \times \overline{\Re}_4$$

In the above, $\overline{\omega}$ and $\overline{\dot{\omega}}$ are obtained from equations (A-1) and (A-5) respectively, and

$$\overline{\Re}_4 = \Re_4 \overline{n}_4 \qquad \text{(D-3)}$$

where, in the primed coordinate system (see ref 3 for configuration angles)

$$\overline{n}_4 = \cos \gamma_p \overline{i'} + \sin \gamma_p \overline{j'} \qquad \text{(D-4)}$$

After transformation into the X-Y-Z system with the help of equations (A-9) and (A-10) and some trigonometric rearrangement, the following is obtained

$$\overline{n}_4 = -\cos\left(\gamma'_p + \beta_3\right)\overline{i} - \sin\left(\gamma'_p + \beta_3\right)\overline{j} \qquad \text{(D-5)}$$

Equation D-3 may now be written as

$$\overline{\Re}_4 = \Re_{4x}\overline{i} + \Re_{4y}\overline{j} = -\Re_4 \cos\left(\gamma'_p + \beta_3\right)\overline{i} - \Re_4 \sin\left(\gamma'_p + \beta_3\right)\overline{j} \qquad \text{(D-6)}$$

With the above, equation D-2 is now evaluated

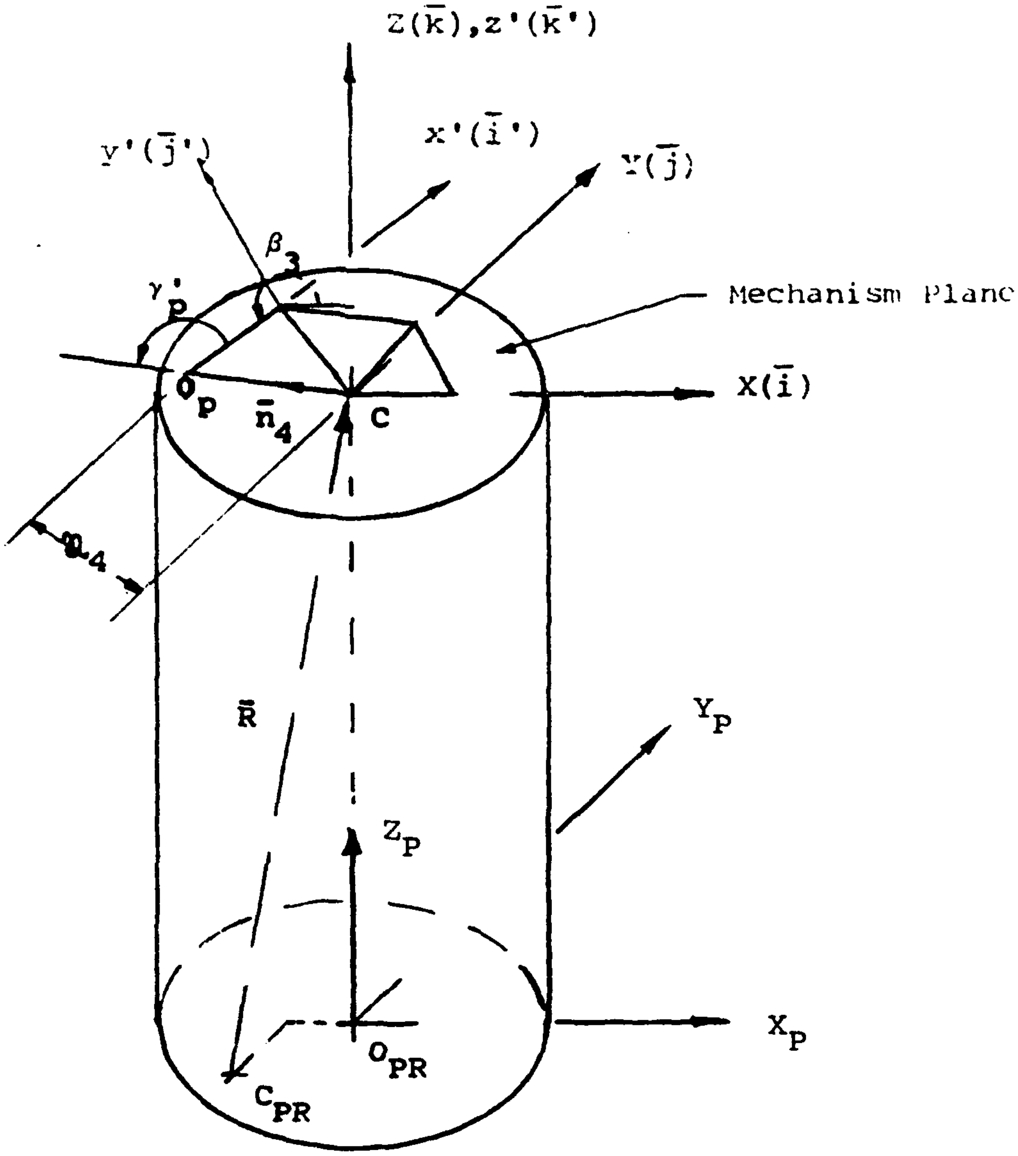
$$\overline{A}_{O_p/C} = H_x\overline{i} + H_y\overline{j} + H_z\overline{k} \qquad \text{(D-7)}$$

where

$$H_x = [\Re_{4y}\omega_x\omega_y - \Re_{4x}(\omega_y^2 + \omega_z^2) - \Re_{4y}\,\dot{\omega}_z] \qquad \text{(D-8)}$$

$$H_y = [\Re_{4x}\omega_x\omega_y - \Re_{4y}(\omega_x^2 + \omega_z^2) - \Re_{4x}\,\dot{\omega}_z] \qquad \text{(D-9)}$$

$$H_z = [(\Re_{4x}\omega_x + \Re_{4y}\omega_y)\omega_z + (\Re_{4y}\dot{\omega}_x - \Re_{4x}\,\dot{\omega}_y)] \qquad \text{(D-10)}$$



C_{PR} = Projectile Center of Mass

C = Geometric Center of Mechanism Plane

Figure D-2. Relationship between mechanism plane-fixed x'-y'-z' and X-Y-Z systems (the mechanism plane is part of projectile)

The acceleration $A_{O_p/ground}$ is evaluated according to equation D-1 with the help of equations C-4 and D-7, i.e.,

$$\bar{A}_{O_p/ground} = (G_x + H_x)\bar{i} + (G_y + H_y)\bar{j} + (G_z + H_z)\bar{k} \tag{D-11}$$

For later computational convenience, the above expression is transformed into the x′-y′-z′ system

$$\bar{A}_{O_p/ground} = K_x\bar{i}' + K_y\bar{j}' + K_z\bar{k}' \tag{D-12}$$

where

$$K_x = (G_x + H_x)\cos\beta_3 - (G_y + H_y)\sin\beta_3 \tag{D-13}$$

$$K_y = (G_x + H_x)\sin\beta_3 - (G_y + H_y)\cos\beta_3 \tag{D-14}$$

$$K_z = G_z + H_z \tag{D-15}$$

Acceleration of Pallet Center of Mass C_p with Respect to Pallet Pivot O_p

When the relative acceleration of the pallet center or mass with respect to the pallet pivot is formulated in terms of the pallet-fixed ξ_p - η_p - ζ_p coordinate system, the following is obtained (fig. D-3):

$$\bar{A}_{C_p/O_p} = \bar{\omega}_{p/a} x(\bar{\omega}_{p/a} x r_{cp}\bar{n}_{\xi_p}) + \bar{\dot{\omega}}_{p/a} x\, r_{cp}\bar{n}_{\xi_p} \tag{D-16}$$

where

$$\bar{\omega}_{p/a} = \omega_{\xi_p}\bar{n}_{\xi_p} + \omega_{\eta_p}\bar{n}_{\eta_p} + \omega_{\zeta_p}\bar{n}_{\zeta_p} \qquad \text{(see eq. A-23)}$$

$$\bar{\dot{\omega}}_{p/a} = \dot{\omega}_{\xi_p}\bar{n}_{\xi_p} + \dot{\omega}_{\eta_p}\bar{n}_{\eta_p} + \dot{\omega}_{\zeta_p}\bar{n}_{\zeta_p} \qquad \text{(see eq. A-27)}$$

$$r_{cp} = O_p - C_p$$

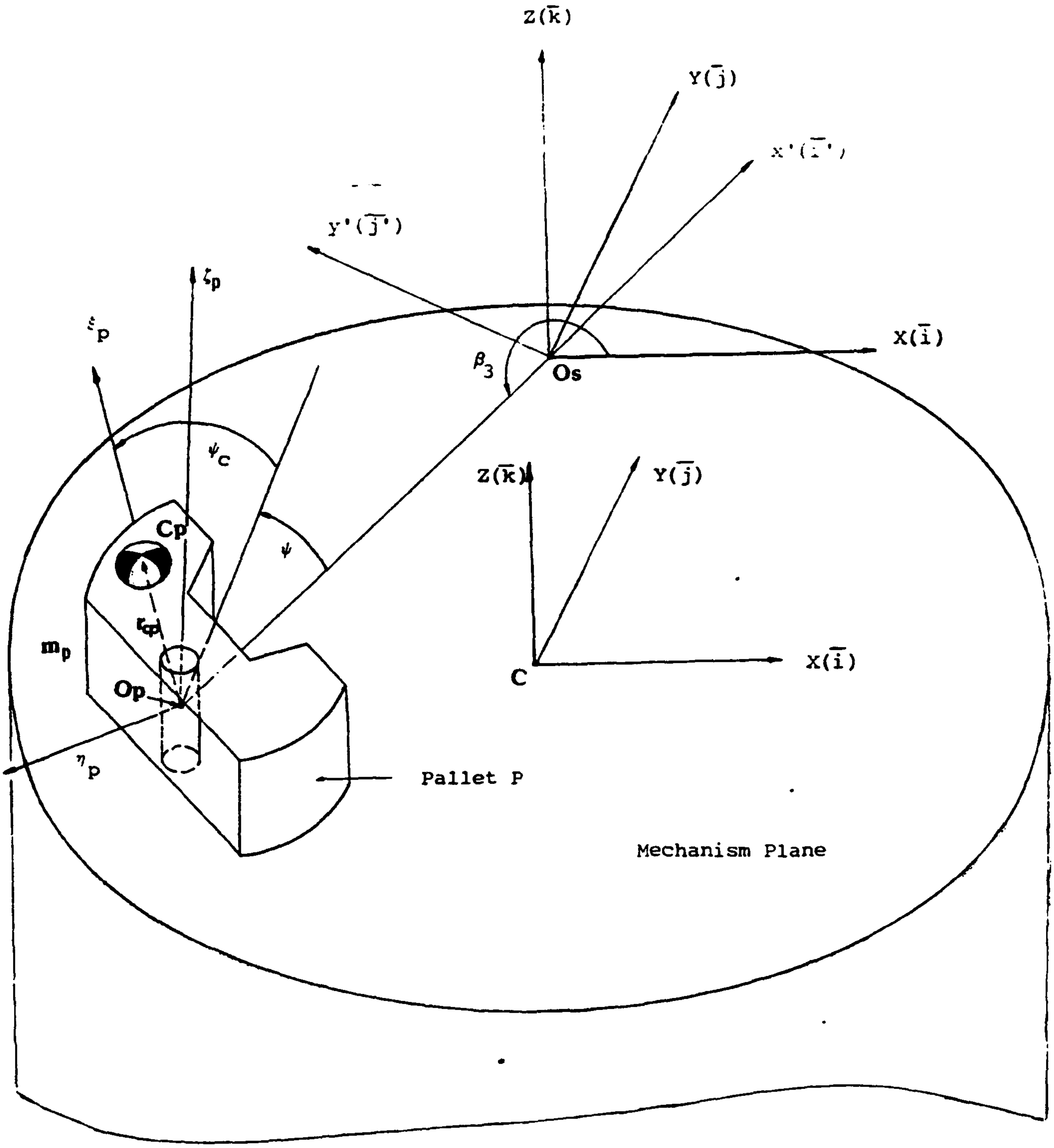


Figure D-3. Pallet center of mass C_p and pallet pivot O_p

Appropriate substitution and evaluation of equation D-16 furnishes

$$\bar{A}_{C_p/O_p} = r_{c_p}\{[-(\omega_x \sin\alpha' - \omega_y \cos\alpha')^2 - (\omega_z + \dot{\psi})^2]\bar{n}_{\xi_p} + [\sin\alpha'\cos\alpha'(\omega_y^2 - \omega_x^2)$$

$$+ \omega_x\omega_y (\cos^2\alpha' - \sin^2\alpha') + \dot{\omega}_z + \ddot{\psi}]\bar{n}_{\eta_p} + [-\sin\alpha'(\dot{\omega}_x + 2\omega_y\dot{\psi} + \omega_y\omega_z)$$

$$+ \cos\alpha' (\dot{\omega}_y - 2\omega_x\dot{\psi} - \omega_x\omega_z)]\bar{n}_{\zeta_p}\} \tag{D-17}$$

The above expression is now transformed into the x′-y′-z′ system (again for later computational convenience) with the help of equations A-11, A-12, and A-14

$$\bar{A}_{C_p/O_p} = T_x\bar{i}' + T_y\bar{j}' + T_z\bar{k}' \tag{D-18a}$$

where

$$T_x = r_{cp}[-\omega_x^2\sin\beta_3 \sin\alpha' - \omega_y^2\cos\beta_3 \cos\alpha' + \omega_x\omega_y \sin(\alpha' + \beta_3)$$

$$- (\omega_z + \dot{\psi})^2\cos\beta - (\dot{\omega}_z + \ddot{\psi}) \sin\beta] \tag{D-18b}$$

$$T_y = r_{cp}[-\omega_x^2\cos\beta_3 \sin\alpha' + \omega_y^2 \sin\beta_3\cos\alpha' + \omega_x\omega_y \cos(\alpha' + \beta_3)$$

$$- (\omega_z + \dot{\psi})^2\sin\beta + (\dot{\omega}_z + \ddot{\psi}) \cos\beta] \tag{D-18c}$$

$$T_z = r_{cp}\left[-\sin\alpha'\left(\dot{\omega}_x + 2\omega_y\dot{\psi} + \omega_y\omega_z\right) + \cos\alpha'\left(\dot{\omega}_y - 2\omega_x\dot{\psi} - \omega_x\omega_z\right)\right] \tag{D-18d}$$

Absolute Acceleration of Pallet Center of Mass C_p

The total acceleration of the pallet center of mass is given by

$$\bar{A}_{C_p/ground} = \bar{A}_{C_p/O_p} + \bar{A}_{O_p/ground} \tag{D-19}$$

Substitution of equations D-12 and D-18a into the above yields the following expression

$$\bar{A}_{C_p/ground} =$$

$$\{r_{cp}[-\omega_x^2 \sin\beta_3 \sin\alpha' - \omega_y^2 \cos\beta_3 \cos\alpha' + \omega_x\omega_y \sin(\alpha' + \beta_3) - (\omega_z + \dot{\psi})^2 \cos\beta$$

$$- (\dot{\omega}_z + \ddot{\psi}) \sin\beta] + K_x\} \bar{i}' + \{r_{cp}[-\omega_x^2 \cos\beta_3 \sin\alpha' + \omega_y^2 \sin\beta_3 \cos\alpha' - \omega_x\omega_y$$

$$\cos(\alpha' + \beta_3) - (\omega_z + \dot{\psi})^2 \sin\beta + (\dot{\omega}_z + \ddot{\psi}) \cos\beta] + K_y\}\bar{j}' + \{r_{cp}[-(\dot{\omega}_x + \omega_y\omega_z)$$

$$\sin\alpha' + (\dot{\omega}_y - \omega_x\omega_z) \cos\alpha' - 2\dot{\psi}(\omega_x \cos\alpha' + \omega_y \sin\alpha')] + K_z\}\bar{k}' \qquad \text{(D-20)}$$

Signum Functions

Before deriving the equations of motion of the pallet and the escape wheel, it is necessary to introduce two signum functions which will be used to determine the directions of the friction forces at the pallet-escape wheel interface and at the pallet pivots, respectively (ref 1).

The relationship between the contact point S on the escape wheel and the coincident point T on the pallet is shown in figure D-4a. The signum function s_4 makes use of the relative velocity $V_{S/T}$; i.e., (see ref 1)

$$s_4 = \frac{V_{S/T}}{|V_{S/T}|} \qquad \text{(D-21)}$$

The signum function s_5, which is associated with pallet rotation, is defined by

$$s_5 = \frac{\dot{\psi}}{|\dot{\psi}|} \qquad \text{(D-22)}$$

Pallet and Escape Wheel in Entrance Coupled Motion

A free body diagram of the pallet with the normal force P_n and the fraction force μP_n acting on its entrance working surface is shown in figure D-4a. The normal and friction forces acting on the upper and lower pivots of the pallet are shown in figure D-4b. For verge nomenclature see reference 1.

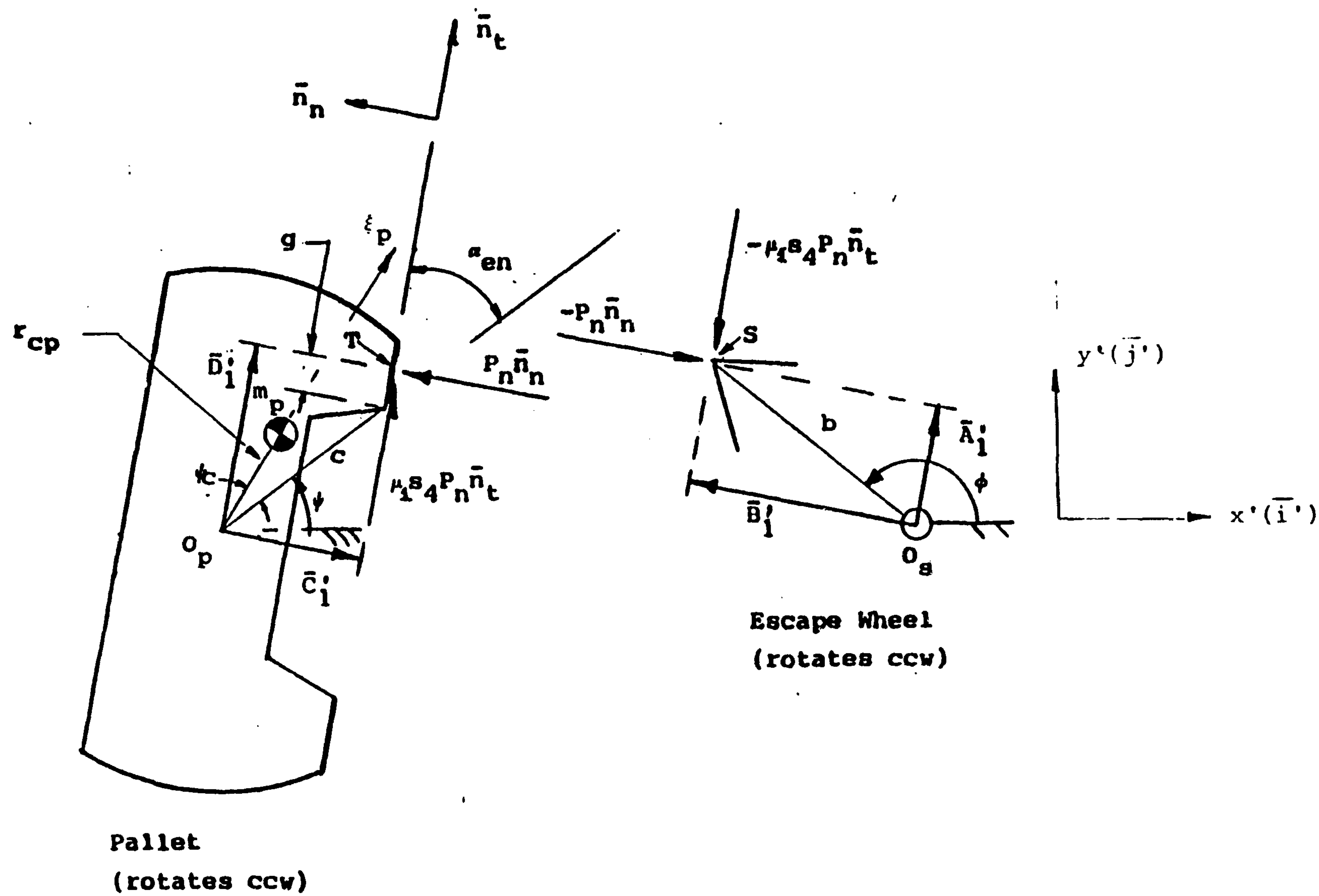


Figure D-4a. Top view free body diagram of pallet in entrance coupled motion

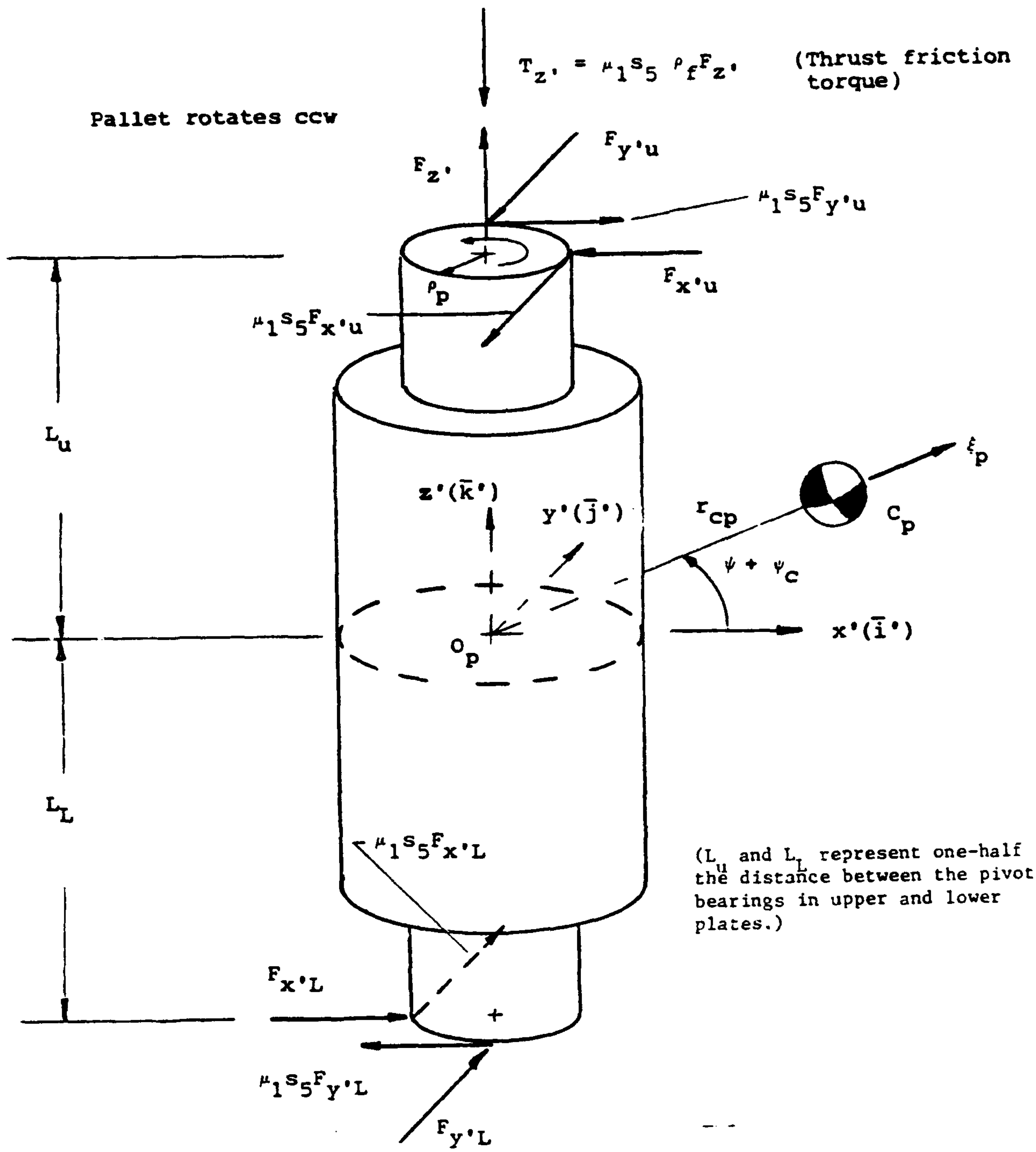


Figure D-4b. Pallet in entrance coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots.

Force Equations for Pallet

The force equations for the pallet in entrance coupled motion are obtained from Newton's law according to

$$\Sigma \bar{F} = m_p \bar{A}_{C_p/\text{ground}} \tag{D-23}$$

where the acceleration $\bar{A}_{C_p/\text{ground}}$ of the pallet center of mass is given by equation D-20. The sum of the forces is obtained with the help of the figures mentioned. (For escapement forces, see equation B-43 of reference 1.) Equation D-23 becomes

$$
\begin{aligned}
& P_n\bar{n}_n + \mu_1 s_4 P_n \bar{n}_t + F_z'\bar{k}' - F_{x'u}\bar{i}' - F_{y'u}\bar{j}' - \mu_1 s_5 F_{x'u}\bar{j}' + s_5\mu_1 F_{y'u}\bar{i}' + F_{x'L}\bar{i}' + F_{y'L}\bar{j}' \\
& + \mu_1 s_5 F_{x'L}\bar{j}' - \mu_1 s_5 F_{y'L}\bar{i}' = m_p \Big[\Big\{r_{cp}\big[-\omega_x^2\cos\beta_3 \sin\alpha' - \omega_y^2\cos\beta_3\cos\alpha' \\
& + \omega_x\omega_y\sin(\alpha' + \beta_3) - (\omega_z + \dot\psi)^2\cos\beta - (\dot\omega_z + \ddot\psi)\sin\beta\big] + K_x\Big\}\bar{i}' \\
& + \{r_{cp}[-\omega_x^2\cos\beta_3\sin\alpha' + \omega_y^2\sin\beta_3\cos\alpha' - \omega_x\omega_y\cos(\alpha' + \beta_3) \\
& - (\omega_z + \dot\psi)^2 \sin\beta + (\dot\omega_z + \ddot\psi)\cos\beta] + K_y\}\bar{j}' + \{r_{cp}[(\dot\omega_x + \omega_y\omega_z)\sin\alpha' \\
& + (\dot\omega_y - \omega_x\omega_z)\cos\alpha' - 2\dot\psi_p(\omega_x\cos\alpha' + \omega_y\sin\alpha')] + K_z\}\,\bar{k}'\Big]
\end{aligned} \tag{D-24}
$$

where $F_{x'u}$ and $F_{y'u}$ are the normal force components acting on the upper pivot, $F_{x'L}$ and $F_{y'L}$ act on the lower pivot, and $F_{z'}$ represents a thrustforce exerted on the pivot shaft.

Note that, as in reference 1, the force and moment equations of the pallet are given in the x′-y′-z′ system for computation convenience.

The unit vectors $\bar{n}_t$ and $\bar{n}_n$ are expressed according to equations C-5 and C-6 of reference 1 in the primed system as follows

$$\bar{n}_t = \cos(\psi + \alpha)\bar{i}' + \sin(\psi + \alpha)\bar{j}' \tag{D-25}$$

$$\bar{n}_n = -\sin(\psi + \alpha)\,\bar{i}' + \cos(\psi + \alpha)\,\bar{j}' \tag{D-26}$$

The angle α is associated with the pallet and is different for entrance and exit contact.

Substitution of equations D-25 and D-26 into equation D-24 furnishes the following component expressions

x' - component of force equation

$$-P_n\sin(\psi + \alpha) + \mu_l s_4 P_n\cos(\psi + \alpha) - F_{x'_u} + \mu_l s_5 F_{y'_u} + F_{x'_L} - \mu_l s_5 F_{y'_L}$$

$$= m_p\{r_{cp}[-\omega_x^2\sin\beta_3\sin\alpha' - \omega_y^2\cos\beta_3\cos\alpha' + \omega_x\omega_y\sin(\alpha' + \beta_3)$$

$$- (\omega_z + \dot{\psi})^2\cos\beta - (\dot{\omega}_z + \ddot{\psi})\sin\beta] + K_x\} \qquad \text{(D-27)}$$

y' - component of force equation

$$P_n\cos(\psi + \alpha) + \mu_l s_4 P_n\sin(\psi + \alpha) - F_{y'_u} - \mu_l s_5 F_{x'_u} + F_{y'_L} + \mu_l s_5 F_{x'_L}$$

$$= m_p\{r_{cp}[-\omega_x^2\cos\beta_3\sin\alpha' + \omega_y^2\sin\beta_3\cos\alpha' - \omega_x\omega_y$$

$$\cos(\alpha' + \beta_3) - (\omega_z + \dot{\psi}_p)^2\sin\beta + (\dot{\omega}_z + \ddot{\psi})\cos\beta] + K_y\} \qquad \text{(D-28)}$$

z' - component of force equation

$$F_{z'} = m_p\{r_{cp}[-(\dot{\omega}_x + \omega_y\omega_z)\sin\alpha' + (\dot{\omega}_y - \omega_x\omega_z)\cos\alpha' - 2\dot{\psi}(\omega_x\cos\alpha'$$

$$+ \omega_y\sin\alpha')] + K_z\} \qquad \text{(D-29)}$$

Moment Equation for the Pallet

The moment equation for the pallet must be written with respect to the accelerated pivot point O_p

$$\overline{M}_{O_p} = -\overline{A}_{O_p/ground} \times m_p r_{cp}(\cos\beta\bar{i}' + \sin\beta\bar{j}') + \dot{\overline{H}}_{O_p x'y'z'} \qquad \text{(D-30)}$$

where $\overline{M}_{O_p}$ is the sum of external moments about point O_p. It is assumed that O_p lies in the plane of the center of mass of the verge (normal to the verge pivot axis). It is also

assumed that the forces $\bar{P}_n$ and $\overline{\mu_l s_4 P}_n$ lie in this plane. $\bar{A}_{O_p/ground}$ is the absolute acceleration of point O_p according to equation D-12. $\dot{\bar{H}}_{O_p x'y'z'}$ is the rate of change of the angular momentum of the verge with respect ot point O_p. This expression is obtained by adapting equation B-4 to the parameters of the pallet and transforming the result into the x'y'z' system.

Determination of $\bar{M}_{O_p}$

The moments due to the verge contact force $\bar{P}_n$ and the associated friction force $\overline{\mu_l s_4 P_n}$ are taken from equation B-48 of reference 1. The moments due to the pivot forces, both normal and frictional, are obtained with the help of the figure D-4b. The symbols ρ_p and ρ_f stand for the pallet pivot radius and the pallet thrust friction radius, respectively.[2] Therefore,

$$
\begin{aligned}
\bar{M}_{O_p} = {} & D_l' P_n \bar{k}' - \mu_l s_4 C_l' P_n \bar{k}' - \mu_l s_5 \rho_f F_{z'} \bar{k}' \\
& + (L_u \bar{k}' + \rho_p \bar{j}') \times (-F_{y'u} \bar{j}' + \mu_l s_5 F_{y'u} \bar{i}') \\
& + (L_u \bar{k}' + \rho_p \bar{i}') \times \left(-F_{x'u} \bar{i}' - \mu_l s_5 F_{x'u} \bar{j}'\right) \\
& + (-L_L \bar{k}' - \rho_p \bar{j}') \times \left(F_{y'L} \bar{j}' - \mu_l s_5 F_{y'L} \bar{i}'\right) \\
& + \left(-L_L \bar{k}' - \rho_p \bar{i}'\right) \times (F_{x'L} \bar{i}' + \mu_l s_5 F_{x'L} \bar{j}')
\end{aligned} \tag{D-31}
$$

The above becomes

$$
\begin{aligned}
\bar{M}_{O_p} = {} & [L_u F_{y'u} + L_u \mu_l s_5 F_{x'u} + L_L F_{y'L} + L_L \mu_l s_5 F_{x'L}] \bar{i}' \\
& + [L_u \mu_l s_5 F_{y'u} - L_u F_{x'u} + L_L \mu_l s_5 F_{y'L} - L_L F_{x'L}] \bar{j}' \\
& + [P_n (D_l' - \mu s_4 C_l') - \mu_l \rho_f s_5 F_{z'} - \rho_p \mu_l s_5 F_{y'u} - \rho_p \mu_l s_5 F_{x'u} \\
& - \rho_p \mu_l s_5 F_{y'L} - \rho_p \mu_l s_5 F_{x'L}] \bar{k}'
\end{aligned} \tag{D-32}
$$

[2] Reference 3 for determination of thrust friction radius, p 268.

Determination of $-\bar{A}_{O_p/ground}\, x m_p r_{cp} (\cos\beta \bar{i}' + \sin\beta \bar{j}')$

With the help of equation D-12, for the above cross-product the following is obtained

$$-(K_x\bar{i}' + K_y\bar{j}' + K_z\bar{k}')x m_p r_{cp}(\cos\beta\bar{i}' + \sin\beta\bar{j}')$$

$$= m_p r_{cp} K_z \sin\beta \bar{i}' - m_p r_{cp} K_z \cos\beta \bar{j}' - m_p r_{cp}(K_x \sin\beta - K_y \cos\beta)\bar{k}' \tag{D-33}$$

Determination of $\bar{H}_{O_p x'y'z'}$

As stated earlier, equation B-4 must first be adapted to the pallet-fixed coordinate system with pallet related nomenclature. This leads to

$$\begin{aligned}
\bar{H}_{O_p} = [&I_{\xi\xi_p}\dot{\omega}_\xi + \omega_\eta\omega_\zeta(I_{\zeta\zeta_p} - I_{\eta\eta_p}) + I_{\xi\eta_p}(\omega_\zeta\omega_\xi - \dot{\omega}_\eta) \\
&+ I_{\zeta\xi_p}(\dot{\omega}_\zeta + \omega_\xi\dot{\omega}_\eta) + I_{\eta\zeta}\left(\omega_\eta{}^2 - \omega_\zeta{}^2\right)]\,\bar{n}_{\xi_p} \\
&+ [I_{\eta\eta_p}\dot{\omega}_\eta + \omega_\xi\omega_\zeta(I_{\xi\xi_p} - I_{\zeta\zeta_p}) + I_{\eta\zeta_p}(\omega_\xi\omega_\eta - \dot{\omega}_\zeta) \\
&- I_{\xi\eta_p}(\dot{\omega}_\xi + \omega_\eta\omega_\zeta) - I_{\zeta\xi}\left(\omega_\zeta^2 - \omega_\xi^2\right)]\,\bar{n}_{\eta_p} \\
&+ [I_{\zeta\zeta_p}\dot{\omega}_\zeta + \omega_\xi\omega_\eta(I_{\eta\eta_p} - I_{\xi\xi_p}) + I_{\zeta\xi_p}(\omega_\eta\omega_\zeta - \dot{\omega}_\xi) \\
&- I_{\eta\zeta_p}\left(\dot{\omega}_\eta + \omega_\xi\omega_\zeta\right) - I_{\xi\eta_p}\left(\omega_\xi^2 - \omega_\eta^2\right)]\,\bar{n}_{\zeta_p}
\end{aligned} \tag{D-34}$$

The angular velocities and accelerations of the pallet are now expressed according to equations A-24 to A-26 and equations A-28 to A-30, respectively. Subsequently, the unit vectors $\bar{n}_\xi$, $\bar{n}_\eta$, and $\bar{n}_\zeta$ are substituted according to equations A-11, A-12, and A-17.

These operations result in the following component expressions for $\dot{\bar{H}}_{O_p x'y'z'}$

$$\dot{\bar{H}}_{O_p x'} = A_1 + A_2\dot{\psi} + A_3\dot{\psi}^2 + A_4\ddot{\psi} \tag{D-35}$$

$$\dot{\bar{H}}_{O_p y'} = A_5 + A_6\dot{\psi} + A_7\dot{\psi}^2 + A_8\ddot{\psi} \tag{D-36}$$

$$\dot{\bar{H}}_{O_p z'} = A_9 + A_{10}\ddot{\psi} \tag{D-37}$$

where

$$\begin{aligned}
A_1 = {} & \cos\beta\{-I_{\xi\xi_p}(\dot{\omega}_x\cos\alpha' + \dot{\omega}_y\sin\alpha') + (I_{\zeta\zeta_p} - I_{\eta\eta_p})\omega_z(\omega_x\sin\alpha' \\
& - \omega_y\cos\alpha') - I_{\xi\eta_p}[\omega_z(\omega_x\cos\alpha' + \omega_y\sin\alpha') + (\dot{\omega}_x\sin\alpha' - \dot{\omega}_y\cos\alpha') \\
& + I_{\zeta\xi_p}[(\omega_x\cos\alpha' + \omega_y\sin\alpha')\ (\omega_x\sin\alpha' - \omega_y\cos\alpha') - \dot{\omega}_z] \\
& - I_{\eta\zeta_p}[(\omega_x\sin\alpha' - \omega_y\cos\alpha')^2 - \omega_z^2]\} - \sin\beta\,\{I_{\eta\eta_p}(\dot{\omega}_x\sin\alpha' - \dot{\omega}_y\cos\alpha'] \\
& - (I_{\xi\xi_p} - I_{\zeta\zeta_p})\omega_z(\omega_x\cos\alpha' + \omega_y\sin\alpha') - I_{\eta\zeta_p}[(\omega_x\cos\alpha' + \omega_y\sin\alpha') \\
& (\omega_x\sin\alpha' - \omega_y\cos\alpha') + \dot{\omega}_z] + I_{\xi\eta_p}[(\dot{\omega}_x\cos\alpha' + \dot{\omega}_y\sin\alpha') - \omega_z(\omega_x\sin\alpha' \\
& - \omega_y\cos\alpha')] - I_{\zeta\xi_p}[\omega_z^2 - (\omega_x\cos\alpha' + \omega_y\sin\alpha')^2]\}
\end{aligned} \tag{D-38}$$

$$\begin{aligned}
A_2 = {} & (\omega_x\sin\alpha' - \omega_y\cos\alpha')[(I_{\xi\xi_p} + I_{\zeta\zeta_p} - I_{\eta\eta_p})\cos\beta + 2\,I_{\xi\eta_p}\sin\beta] \\
& - (\omega_x\cos\alpha' + \omega_y\sin\alpha')\left[2\,I_{\xi\eta_p}\cos\beta + (I_{\eta\eta_p} - I_{\xi\xi_p} + I_{\zeta\zeta_p})\sin\beta\right] \\
& + 2\,\omega_z(I_{\eta\zeta_p}\cos\beta + I_{\zeta\xi_p}\sin\beta)
\end{aligned} \tag{D-39}$$

$$A_3 = I_{\eta\zeta_p}\cos\beta + I_{\zeta\xi_p}\sin\beta \tag{D-40}$$

$$A_4 = I_{\eta\zeta_p}\sin\beta - I_{\zeta\xi_p}\cos\beta \tag{D-41}$$

$$\begin{aligned}
A_5 = {} & \sin\beta\{-I_{\xi\xi_p}(\dot{\omega}_x\cos\alpha' + \dot{\omega}_y\sin\alpha') + (I_{\zeta\zeta_p} - I_{\eta\eta_p})\omega_z(\omega_x\sin\alpha' \\
& - \omega_y\cos\alpha') + I_{\xi\eta p}[- \omega_z(\omega_x\cos\alpha' + \omega_y\sin\alpha') - (\dot{\omega}_x\sin\alpha' - \dot{\omega}_y\cos\alpha')] \\
& - I_{\zeta\xi_p}[-(\omega_x\cos\alpha' + \omega_y\sin\alpha')(\omega_x\sin\alpha' - \omega_y\cos\alpha') + \dot{\omega}_z] \\
& - I_{\eta\zeta_p}[(\omega_x\sin\alpha' - \omega_y\cos\alpha')^2 - \omega_z^2]\} + \cos\beta\,\{I_{\eta\eta_p}(\dot{\omega}_x\sin\alpha' - \dot{\omega}_y\cos\alpha'] \\
& - (I_{\xi\xi_p} - I_{\zeta\zeta_p})\omega_z(\omega_x\cos\alpha' + \omega_y\sin\alpha') + I_{\eta\zeta_p}[-(\omega_x\cos\alpha' + \omega_y\sin\alpha') \\
& (\omega_x\sin\alpha' - \omega_y\cos\alpha') - \dot{\omega}_z] - I_{\xi\eta_p}[-(\dot{\omega}_x\cos\alpha' + \dot{\omega}_y\sin\alpha') + \omega_z(\omega_x\sin\alpha' \\
& - \omega_y\cos\alpha')] - I_{\zeta\xi_p}[\omega_z^2 - (\omega_x\cos\alpha' + \omega_y\sin\alpha')^2]\}
\end{aligned} \tag{D-42}$$

$$\begin{aligned}
A_6 = {} & (\omega_x\sin\alpha' - \omega_y\cos\alpha')[(I_{\xi\xi_p} + I_{\zeta\zeta_p} - I_{\eta\eta_p})\ \sin\beta - 2\,I_{\xi\eta_p}\cos\beta] + (\omega_x\cos\alpha' \\
& + \omega_y\sin\alpha')\left[\left(I_{\eta\eta_p} - I_{\xi\xi_p} + I_{\zeta\zeta_p}\right)\cos\beta - 2I_{\xi\eta_p}\sin\beta\right] + 2\omega_z\left(I_{\eta\zeta_p} - I_{\zeta\xi_p}\right)
\end{aligned} \tag{D-43}$$

$$A_7 = I_{\eta\zeta_p}\sin\beta - I_{\zeta\xi_p}\cos\beta \tag{D-44}$$

$$A_8 = -\left(I_{\zeta\xi_p}\sin\beta + I_{\eta\zeta_p}\cos\beta\right) \tag{D-45}$$

$$A_9 = I_{\zeta\zeta_p}\dot{\omega}_z - (I_{\eta\eta_p} - I_{\xi\xi_p})[(\omega_x \cos\alpha' + \omega_y \sin\alpha')(\omega_x \sin\alpha' - \omega_y \cos\alpha')]$$

$$+ I_{\zeta\xi_p}\left[\omega_z\left(\omega_x \sin\alpha' - \omega_y \sin\alpha'\right) + \left(\dot{\omega}_x \cos\alpha' + \dot{\omega}_y \sin\alpha'\right)\right]$$

$$- I_{\eta\zeta_p}[(\dot{\omega}_x \sin\alpha' - \dot{\omega}_y \cos\alpha') - \omega_z(\omega_x \cos\alpha' + \omega_y \sin\alpha')]$$

$$- I_{\xi\eta_p}[(\omega_x \cos\alpha' + \omega_y \sin\alpha')^2 - (\omega_x \sin\alpha' - \omega_y \cos\alpha')^2] \qquad \text{(D-46)}$$

$$A_{10} = I_{\zeta\zeta_p} \qquad \text{(D-47)}$$

Simplification of Force and Moment Equations

In order to be able to solve for the upper and lower pivot forces, both the force and moment component equations are now rewritten in an appropriate simplified form.

x′-Component of the Force Equation

Equation D-27 becomes

$$-F_{x'u} + A_{11}F_{y'u} + F_{x'L} - A_{11}F_{y'L} = A_{12} + A_{13}\dot{\psi} + A_{14}\dot{\psi}^2 + A_{15}\ddot{\psi} + P_n A_{16} \qquad \text{(D-48)}$$

where

$$A_{11} = \mu_1 s_5 \qquad \text{(D-49)}$$

$$A_{12} = m_p r_{cp}[-\omega_x^2 \sin\beta_3 \sin\alpha' - \omega_y^2 \cos\beta_3 \cos\alpha' + \omega_x\omega_y \sin(\alpha' + \beta_3)$$

$$- \omega_z^2 \cos\beta - \dot{\omega}_z \sin\beta] + m_p K_x \qquad \text{(D-50)}$$

$$A_{13} = -2\omega_z m_p r_{cp} \cos\beta \qquad \text{(D-51)}$$

$$A_{14} = -m_p r_{cp} \cos\beta \qquad \text{(D-52)}$$

$$A_{15} = -m_p r_{cp} \sin\beta \qquad \text{(D-53)}$$

$$A_{16} = -[\mu_1 s_4 \cos(\psi + \alpha) - \sin(\psi + \alpha)] \qquad \text{(D-54)}$$

y′-Component of the Force Equation

Equation D-28 becomes

$$-A_{11} F_{x'u} - F_{y'u} + A_{11} F_{x'L} + F_{y'L} = A_{17} + A_{18}\dot{\psi} + A_{19}\dot{\psi}^2 + A_{20}\ddot{\psi} + A_{21} P_n \qquad \text{(D-55)}$$

where

$$A_{17} = m_p r_{cp}[-\omega_x^2 \cos\beta_3 \sin\alpha' + \omega_y^2 \sin\beta_3 \cos\alpha' - \omega_x \omega_y \cos(\alpha' + \beta_3)$$

$$- \omega_z^2 \sin\beta + \dot{\omega}_z \cos\beta] + m_p K_y \qquad \text{(D-56)}$$

$$A_{18} = -2\omega_z m_p r_{cp} \sin\beta \qquad \text{(D-57)}$$

$$A_{19} = -m_p r_{cp} \sin\beta \qquad \text{(D-58)}$$

$$A_{20} = m_p r_{cp} \cos\beta \qquad \text{(D-59)}$$

$$A_{21} = -[\cos(\psi + \alpha) + \mu_1 s_4 \sin(\psi + \alpha)] \qquad \text{(D-60)}$$

z′-Component of the Force Equation

Equation D-29 is rewritten to read

$$\tilde{F}_{z'} = A_{22} + A_{23}\dot{\psi} \qquad \text{(D-61)}$$

The tilde is now used to indicate the conservative nature of this force, when the terms A_{22} and A_{23} are made absolute.

Thus

$$A_{22} = |m_p r_{cp}[-\dot{\omega}_x + \omega_y\omega_z)\sin\alpha' + (\dot{\omega}_y - \omega_x\omega_y)\cos\alpha' + m_p K_z| \qquad \text{(D-62)}$$

and

$$A_{23} = |-2m_p r_{cp}(\omega_x\cos\alpha' + \omega_y\sin\alpha')| \qquad \text{(D-63)}$$

The absolute values in the above expressions will be useful later in equation D-123.

x′-Component of Moment Equation

The x′-component of equation D-30 is obtained with the help of the x′-components of equations D-32 and D-33, as well as equation D-35. Therefore,

$$L_u A_{11} F_{x'u} + L_u F_{y'u} + L_L A_{11} F_{x'L} + L_L F_{y'L} = m_p r_{cp} K_z \sin\beta$$

$$+ A_1 + \dot{\psi} A_2 + \dot{\psi}^2 A_3 + \ddot{\psi} A_4 \qquad \text{(D-64)}$$

y′-Component of Moment Equation

The y′-component of equation D-30 is obtained with the help of the y′-components of equations D-32 and D-33, as well as equation D-36

$$- L_u F_{x'u} + L_u A_{11} F_{y'u} + L_L F_{x'L} + L_L A_{11} F_{y'L} = -m_p r_{cp} K_z \cos\beta$$

$$+ A_5 + A_6\dot{\psi} + A_7\dot{\psi}^2 + A_8\ddot{\psi} \qquad \text{(D-65)}$$

z′-Component of Moment Equation

The z′-component of equation D-30 is composed of the z′-components of equations D-32 and D-33, as well as equation D-37

$$P_n\left(D_1' - \mu_1 s_4 C_1'\right) - \rho_f A_{11} F_{z'} - \rho_p A_{11} F_{y'u} - \rho_p A_{11} F_{x'u} - \rho_p A_{11} F_{y'L} - \rho_p A_{11} F_{x'L}$$

$$= -m_p r_{cp}(K_x \sin\beta - K_y \cos\beta) + A_9 + A_{10}\ddot{\psi} \qquad \text{(D-66)}$$

Solution for the Pallet Pivot Forces. The forces $F_{x'u}$, $F_{y'u}$, $F_{x'L}$, and $F_{y'L}$ are obtained from the simultaneous solution of equations D-48, D-55, D-64, and D-65. The force $F_{z'}$ is given by equation D-61. These five forces are eventually substituted into equation D-66, and the resulting expression is solved for the contact force P_n.

The simultaneous set of equations becomes

$$\begin{bmatrix} -1 & A_{11} & 1 & -A_{11} \\ -A_{11} & -1 & A_{11} & 1 \\ L_uA_{11} & L_u & L_LA_{11} & L_L \\ -L_u & L_uA_{11} & -L_L & L_LA_{11} \end{bmatrix} \begin{bmatrix} F_{x'u} \\ F_{y'u} \\ F_{x'L} \\ F_{y'L} \end{bmatrix} = \begin{bmatrix} B_{p1} \\ B_{p2} \\ B_{p3} \\ B_{p4} \end{bmatrix} \quad \text{(D-67)}$$

where

$$B_{p1} = A_{12} + A_{13}\dot{\psi} + A_{14}\dot{\psi}^2 + A_{15}\ddot{\psi} + P_nA_{16} \quad \text{(D-68)}$$

$$B_{p2} = A_{17} + A_{18}\dot{\psi} + A_{19}\dot{\psi}^2 + A_{20}\ddot{\psi} + P_nA_{21} \quad \text{(D-69)}$$

$$B_{p3} = m_pr_{cp}K_z\sin\beta + A_1 + A_2\dot{\psi} + A_3\dot{\psi}^2 + A_4\ddot{\psi} \quad \text{(D-70)}$$

$$B_{p4} = - m_pr_{cp}K_z\cos\beta + A_5 + A_6\dot{\psi} + A_7\dot{\psi}^2 + A_8\ddot{\psi} \quad \text{(D-71)}$$

Cramer's rule will now be used to determine the four pivot forces $F_{x'u}$, $F_{y'u}$, $F_{x'L}$, and $F_{y'L}$. To this end, the coefficient determinant D must be found first.

Evaluation of the Coefficient Determinant D

The coefficient determinant of equation D-67 is given by

$$D = \begin{vmatrix} -1 & A_{11} & 1 & -A_{11} \\ -A_{11} & -1 & A_{11} & 1 \\ L_uA_{11} & L_u & L_LA_{11} & L_L \\ -L_u & L_uA_{11} & -L_L & L_LA_{11} \end{vmatrix} \quad \text{(D-72)}$$

Evaluation of the above furnishes

$$D = [(L_u + L_L)(1 + A_{11}^2)]^2 \tag{D-73}$$

Since, according to equation D-49

$$A_{11} = \mu_1 s_5 \tag{D-74}$$

and s_5^2 is always equal to unity (eq D-22), the coefficient determinant becomes

$$D = [(L_u + L_L)(1 + \mu_1^2)]^2 \tag{D-75}$$

<u>Evaluation of Pivot Force</u> $\widetilde{F}_{x'u}$

The pivot force $F_{x'u}$ is obtained from

$$F_{x'u} = \frac{D_{F_{x'u}}}{D} \tag{D-76}$$

where

$$D_{F_{x'u}} = \begin{vmatrix} B_{p1} & A_{11} & 1 & -A_{11} \\ B_{p2} & -1 & A_{11} & 1 \\ B_{p3} & L_u & L_L A_{11} & L_L \\ B_{p4} & L_u A_{11} & -L_L & L_L A_{11} \end{vmatrix} \tag{D-77}$$

Evaluation of $D_{F_{x'u}}$ furnishes

$$D_{F_{x'u}} = (L_u + L_L)(1 + A_{11}^2)(-L_L B_{p1} - A_{11} L_L B_{p2} + A_{11} B_{p3} - B_{p4}) \tag{D-78}$$

After substitution of

$$A_{11}^2 = \mu_1^2 \tag{D-79}$$

the following is obtained

$$D_{F_{x'u}} = (L_u + L_L)(1 + \mu_1^2)(-L_L B_{p1} - A_{11} L_L B_{p2} + A_{11} B_{p3} - B_{p4}) \tag{D-80}$$

Subsequently, equations D-49 and D-68 to D-71 are substituted into the above and the coefficients of similar terms are collected and made absolute. The latter is done to get conservative pivot and friction forces. This leads to

$$D_{F_{x'u}} = (L_u + L_L)(1 + \mu_1^2)(C_1 + C_2\dot{\psi} + C_3\dot{\psi}^2 + C_4\ddot{\psi} + C_5 P_n \tag{D-81}$$

where

$$C_1 = |-L_L A_{12} + \mu_1 s_5(A_1 - L_L A_{17}) - A_5 + m_p r_{cp} K_z(\mu_1 s_5 \sin\beta + \cos\beta)| \tag{D-82}$$

$$C_2 = |-L_L A_{13} + \mu_1 s_5(A_2 - L_L A_{18}) - A_6| \tag{D-83}$$

$$C_3 = |-L_L A_{14} + \mu_1 s_5(A_3 - L_L A_{19}) - A_7| \tag{D-84}$$

$$C_4 = |-L_L A_{15} + \mu_1 s_5(A_4 - L_L A_{20}) - A_8| \tag{D-85}$$

$$C_5 = |-L_L A_{16} + \mu_1 s_5 L_L A_{21}| \tag{D-86}$$

Finally, substitution of equations D-75 and D-81 into equation D-76 gives the now tilded pivot force

$$\tilde{F}_{x'u} = \frac{1}{(L_u + L_L)(1 + \mu_1^2)} (C_1 + C_2\dot{\psi} + C_3\dot{\psi}^2 + C_4\ddot{\psi} + C_5 P_n) \tag{D-87}$$

<u>Evaluation of Pivot Force</u> $\tilde{F}_{y'u}$

The pivot force $\tilde{F}_{y'u}$ is obtained with Cramer's rule, i.e.,

$$\tilde{F}_{y'u} = \frac{D_{F_{y'u}}}{D} \tag{D-88a}$$

where

$$D_{F_{y'u}} = \begin{vmatrix} -1 & B_{p1} & 1 & -A_{11} \\ -A_{11} & B_{p2} & A_{11} & 1 \\ L_u A_{11} & B_{p3} & L_L A_{11} & L_L \\ -L_u & B_{p4} & L_L & L_L A_{11} \end{vmatrix}$$

(D-88b)

Evaluation of $D_{F_{y'u}}$ furnishes

$$D_{F_{y'u}} = (L_u + L_L)(1 + A_{11}^2)(A_{11} L_L B_{p1} - L_L B_{p2} + B_{p3} + A_{11} B_{p4}) \qquad \text{(D-89)}$$

and again, with $A_{11} = s_5 \mu_1$

$$D_{F_{y'u}} = (L_u + L_L)(1 + \mu_1^2)(\mu_1 s_5 L_L B_{p1} - L_L B_{p2} + B_{p3} + \mu_1 s_5 B_{p4}) \qquad \text{(D-90)}$$

Appropriate substitution into equation D-88a and proceeding in a manner parallel to that followed in the determination of $\widetilde{F}_{x'u}$, the following is obtained for $\widetilde{F}_{y'u}$

$$\widetilde{F}_{y'u} = \frac{1}{(L_u + L_L)(1 + \mu_1^2)} (C_6 + C_7 \dot{\psi} + C_8 \dot{\psi}^2 + C_9 \ddot{\psi} + C_{10} P_n) \qquad \text{(D-91)}$$

where

$$C_6 = |A_1 - L_L A_{17} + \mu_1 s_5 (L_L A_{12} + A_5) + m_p r_{cp} K_z (\sin\beta - \mu_1 s_5 \cos\beta)| \qquad \text{(D-92)}$$

$$C_7 = |A_2 - L_L A_{18} + \mu_1 s_5 (A_6 + L_L A_{13})| \qquad \text{(D-93)}$$

$$C_8 = |A_3 - L_L A_{19} + \mu_1 s_5 (A_7 + L_L A_{14})| \qquad \text{(D-94)}$$

$$C_9 = |A_4 - L_L A_{20} + \mu_1 s_5 (L_L A_{15} - A_8)| \qquad \text{(D-95)}$$

$$C_{10} = |\mu_1 s_5 L_L A_{16} - L_L A_{21}| \tag{D-96}$$

<u>Evaluation of Pivot Force $F_{x'L}$</u>

The pivot force $F_{x'L}$ is obtained from

$$F_{x'L} = \frac{D_{F_{x'L}}}{D} \tag{D-97}$$

where

$$D_{F_{x'L}} = \begin{vmatrix} -1 & A_{11} & B_{p1} & -A_{11} \\ -A_{11} & -1 & B_{p2} & 1 \\ L_u A_{11} & L_u & B_{p3} & L_L \\ -L_u & L_u A_{11} & B_{p4} & L_L A_{11} \end{vmatrix} \tag{D-98}$$

Evaluation of $D_{F_{x'L}}$ furnishes

$$D_{F_{x'L}} = (L_u + L_L)(1 + A_{11}{}^2)(L_u B_{p1} + L_u A_{11} B_{p2} + A_{11} B_{p3} - B_{p4}) \tag{D-99}$$

and again, with $A_{11} = s_5\,\mu_1$

$$D_{F_{x'L}} = (L_u + L_L)(1 + \mu_1{}^2)(L_u B_{p1} + \mu_1 s_5 L_u B_{p2} + \mu_1 s_5 B_{p3} - B_{p4}) \tag{D-100}$$

Proceeding as before to obtain $\widetilde{F}_{x'L}$, the following is found

$$\widetilde{F}_{x'L} = \frac{1}{(L_u + L_L)(1 + \mu_1^2)} \left(C_{11} + C_{12}\dot{\psi} + C_{13}\dot{\psi}^2 + C_{14}\ddot{\psi} + C_{15} P_n\right) \tag{D-101}$$

where

$$C_{11} = \left|L_u A_{12} - A_5 + \mu_1 s_5(L_u A_{17} + A_1) + m_p r_{cp} K_z(\mu_1 s_5 \sin\beta + \cos\beta)\right| \qquad \text{(D-102)}$$

$$C_{12} = |L_u A_{13} - A_6 + \mu_1 s_5(L_u A_{18} + A_2)| \qquad \text{(D-103)}$$

$$C_{13} = |L_u A_{14} - A_7 + \mu_1 s_5(L_u A_{19} + A_3)| \qquad \text{(D-104)}$$

$$C_{14} = |L_u A_{15} - A_8 + \mu_1 s_5(L_u A_{20} + A_4)| \qquad \text{(D-105)}$$

$$C_{15} = |L_u A_{16} + \mu_1 s_5 L_u A_{21}| \qquad \text{(D-106)}$$

Evaluation of Pivot Force $\tilde{F}_{y'L}$

The pivot force $F_{y'L}$ is obtained from

$$F_{y'L} = \frac{D_{F_{y'L}}}{D} \qquad \text{(D-107)}$$

where

$$D_{F_{y'L}} = \begin{vmatrix} -1 & A_{11} & 1 & B_{p1} \\ -A_{11} & -1 & A_{11} & B_{p2} \\ L_u A_{11} & L_u & L_L A_{11} & B_{p3} \\ -L_u & L_u A_{11} & -L_L & B_{p4} \end{vmatrix} \qquad \text{(D-108)}$$

Evaluation of $D_{F_{y'L}}$ furnishes

$$D_{F_{y'L}} = (L_u + L_L)(1 + A_{11}^2)(-L_u A_{11} B_{p1} + L_u B_{p2} + B_{p3} + A_{11} B_{p4}) \qquad \text{(D-109)}$$

and again, with $A_{11} = s_5 \mu_1$

$$D_{F_{y'L}} = (L_u + L_L)(1 + \mu_1{}^2)(-\mu_1 s_5 L_u B_{p1} + L_u B_{p2} + B_{p3} + \mu_1 s_5 B_{p4}) \quad \text{(D-110)}$$

$F_{y'L}$ is found from equation D-107 in a manner shown earlier

$$\tilde{F}_{y'L} = \frac{1}{(L_u + L_L)(1 + \mu_1^2)} (C_{16} + C_{17}\dot{\psi} + C_{18}\dot{\psi}^2 + C_{19}\ddot{\psi} + C_{20}P_n) \quad \text{(D-111)}$$

where

$$C_{16} = |L_u A_{17} + A_1 + \mu_1 s_5 (A_5 - L_u A_{12}) + m_p r_{cp} K_z(\sin\beta - \mu_1 s_5 \cos\beta)| \quad \text{(D-112)}$$

$$C_{17} = |L_u A_{18} + A_2 + \mu_1 s_5 (A_6 - L_u A_{13})| \quad \text{(D-113)}$$

$$C_{18} = |L_u A_{19} + A_3 + \mu_1 s_5 (A_7 - L_u A_{14})| \quad \text{(D-114)}$$

$$C_{19} = |L_u A_{20} + A_4 + \mu_1 s_5 (A_8 - L_u A_{15})| \quad \text{(D-115)}$$

$$C_{20} = |L_u A_{21} - \mu_1 s_5 L_u A_{16}| \quad \text{(D-116)}$$

Determination of Contact Force P_n in Terms of Pallet Parameters

Substitution of Conservative (Tilded) Pivot Forces into the z′-Moment Equation. Rather than substitute the forces $F_{x'u}$, $F_{y'u}$, $F_{x'L}$, $F_{y'L}$, and $F_{z'L}$ into the z′-moment equation D-66, the associated tilded, conservative expressions, as given by equations D-61, D-87, D-91, D-101, and D-111 are used. To simplify matters, let the sum of $\tilde{F}_{x'u}$, $\tilde{F}_{y'u}$, $\tilde{F}_{x'L}$, and $\tilde{F}_{y'L}$ be first determined

$$\tilde{F}_{x'u} + \tilde{F}_{y'u} + \tilde{F}_{x'L} + \tilde{F}_{y'L} = A_{24} + A_{25}\dot{\psi} + A_{26}\dot{\psi}^2 + A_{27}\ddot{\psi} + A_{28}P_n \quad \text{(D-117)}$$

where

$$A_{24} = \frac{C_1 + C_6 + C_{11} + C_{16}}{L_T(1 + \mu_1^2)} \quad \text{(D-118)}$$

$$A_{25} = \frac{C_2 + C_7 + C_{12} + C_{17}}{L_T(1 + \mu_1^2)} \tag{D-119}$$

$$A_{26} = \frac{C_3 + C_8 + C_{13} + C_{18}}{L_T(1 + \mu_1^2)} \tag{D-120}$$

$$A_{27} = \frac{C_4 + C_9 + C_{14} + C_{19}}{L_T(1 + \mu_1^2)} \tag{D-121}$$

$$A_{28} = \frac{C_5 + C_{10} + C_{15} + C_{20}}{L_T(1 + \mu_1^2)} \tag{D-122a}$$

and

$$L_T = L_u + L_L \tag{D-122b}$$

Substitution of the above, as well as equation D-61 into equation D-66, and letting $A_{11} = \mu_1 s_5$ according to equation D-49 leads to the following provisional z'-moment expression

$$P_n\left(D_1' - \mu_1 s_4 C_1'\right) - \rho_f \mu_1 s_5\left(A_{22} \pm A_{23}\dot{\psi}\right) - \rho_p \mu_1 s_5\Big(A_{24} \pm \dot{\psi} A_{25} \pm \dot{\psi}^2 A_{26}$$

$$\pm \ddot{\psi} A_{27} + P_n A_{28}\Big) = -\, m_p r_{cp}\left(K_x \sin\beta - K_y \cos\beta\right) + A_9 + A_{10}\ddot{\psi} \tag{D-123}$$

To make sure that all friction moments act in a direction opposite to the instantaneous rotation of the pallet, the signs of those friction terms which depend on ψ, $\dot{\psi}$, or $\ddot{\psi}$ have been left undecided for the moment. They will be resolved below.

Before these decisions are made, let equation D-123 be written as follows

$$P_n\left(D_1' - C_1'\mu_1 s_4 - \rho_p \mu_1 s_5 A_{28}\right) - \mu_1 s_5\left(\rho_f A_{22} + \rho_p A_{24}\right) \pm \mu_1 s_5$$

$$\left(\rho_f A_{23} + \rho_p A_{25}\right)\dot{\psi} \pm \rho_p \mu_1 s_5 A_{26} \dot{\psi}^2 \pm \rho_p \mu_1 s_5 A_{27} \ddot{\psi}$$

$$= A_{10}\ddot{\psi} + A_9 - m_p r_{cp}(K_x \sin\beta - K_y \cos\beta) \tag{D-124}$$

With s_5 positive for positive rotation of the verge and vice versa and with all other parameters positive at all times, the following moment components of equation D-124 must have negative signs during positive rotation

$$-P_n \rho_p \mu_1 s_5 A_{28} \tag{D-125}$$

$$-\mu_1 s_5(\rho_f A_{22} + \rho_p A_{24}) \tag{D-126}$$

$$-\rho_p \mu_1 s_5 A_{26} \dot{\psi}^2 \tag{D-127}$$

The sign of the term containing $\dot{\psi}$ must be negative for a positive $\dot{\psi}$ and vice versa. Therefore, the sign of $\dot{\psi}$ can be used to control the sign of this term, and the signum operator s_5 has been omitted. This term becomes

$$-\mu_1(\rho_f A_{23} + \rho_p A_{25})\dot{\psi} \tag{D-128}$$

The choice of sign for the term containing the pallet angular acceleration is discussed in detail in appendix F of reference 4. This work leads to the computational rules of equations D-134 and D-135 below. These rules deal with the sign in the effective moment of inertia I_{PR}. (Note that the signum function s_5 has been omitted in these expressions.)

With the above considerations, equation D-124 becomes

$$P_n A_{29} - A_{30} - A_{31}\dot{\psi} - A_{32}\dot{\psi}^2 = I_{PR}\ddot{\psi} + A_9 - m_p r_{cp}(K_x \sin\beta - K_y \cos\beta) \tag{D-129}$$

where

$$A_{29} = D_1' - C_1' \mu_1 s_4 - \rho_p \mu_1 s_5 A_{28} \tag{D-130}$$

$$A_{30} = \mu_1 s_5(\rho_f A_{22} + \rho_p A_{24}) \tag{D-131}$$

$$A_{31} = \mu_1(\rho_f A_{23} + \rho_p A_{25}) \tag{D-132}$$

$$A_{32} = \mu_1 s_5 \rho_p A_{26} \tag{D-133}$$

$$I_{PR} = I_{\zeta\zeta_p} + A_{333}, \text{ when } \dot{\psi} \text{ and } \ddot{\psi} \text{ have identical signs} \tag{D-134}$$

$$I_{PR} = I_{\zeta\zeta_p} - A_{333}, \text{ when } \dot{\psi} \text{ and } \ddot{\psi} \text{ have opposite signs}^{3} \qquad \text{(D-135)}$$

$$A_{333} = \mu_1 \rho_p A_{27} \qquad \text{(D-136)}$$

Equation D-129 is now rewritten to find an expression for the contact force P_n

$$P_n = \frac{I_{PR}\ddot{\psi} + A_9 + A_{30} + A_{31}\dot{\psi} + A_{32}\dot{\psi}^2 - m_p r_{cp}(K_x \sin\beta - K_y \cos\beta)}{A_{29}} \qquad \text{(D-137)}$$

The above expression is now changed to reflect the escape wheel angular velocity and angular acceleration $\dot{\phi}$ and $\ddot{\phi}$, *respectively, so that it may later be equated to an expression* for the escape wheel. Equations C-19 and C-26 of appendix C of reference 1 show the following relationships

$$\dot{\psi} = \dot{\phi}U \qquad \text{(D-138)}$$

and

$$\ddot{\psi} = U\ddot{\phi} + V\dot{\phi}^2 \qquad \text{(D-139)}$$

U and V may also be obtained from reference 1. This leads to

$$P_n = \frac{1}{A_{29}}[I_{PR}U\ddot{\phi} + (A_{32}U^2 + I_{PR}V)\dot{\phi}^2 + A_{31}U\dot{\phi} + A_9 + A_{30}$$

$$- m_p r_{cp}(K_x \sin\beta - K_y \cos\beta)] \qquad \text{(D-140)}$$

Force Equations for Escape Wheel and Pinion No. 3 with Mesh 2 in Round-on-Round-Contact (see reference 1, for clock tooth force analysis background)

The action of the contact forces $\bar{P}_n$ and $\bar{F}_{23}$, together with their associated friction forces are shown in figure D-5a. A separate free body diagram of the pivot shaft of the escape wheel is shown in figure D-5b.

---

[3] I_p - A_{333} must not become negative. If this occurs I_{PR} must be set equal to zero.

All forces must now be expressed in terms of the mechanism plane-fixed X - Y - Z system. This makes it necessary to transform the unit vectors $\bar{n}_t$ and $\bar{n}_n$ from the X′ - Y′ system into the X-Y one. (See eqs B-16 and B-17, as well as eqs B-79 to B-82 of reference 1.)

Since

$$\bar{i}' = -\cos\beta_3\bar{i} - \sin\beta_3\bar{j} \tag{D-141}$$

and

$$\bar{j}' = \sin\beta_3\bar{i} - \cos\beta_3\bar{j} \tag{D-142}$$

the previous unit vectors become

$$\bar{n}_t = -\cos(\psi + \alpha + \beta_3)\,\bar{i} - \sin(\psi + \alpha + \beta_3)\bar{j} \tag{D-143}$$

$$\bar{n}_n = \sin(\psi + \alpha + \beta_3)\,\bar{i} - \cos(\psi + \alpha + \beta_3)\bar{j} \tag{D-144}$$

Further, the round-on-round contact force F_{23} has the direction of the unit $\bar{n}_{\lambda 2}$ vector so that

$$\bar{F}_{23} = F_{23}\bar{n}_{\lambda 2} \tag{D-145a}$$

where, according to equation G-48 of reference 5

$$\bar{n}_{\lambda 2} = \cos\lambda_2\bar{i} + \sin\lambda_2\bar{j} \tag{D-145b}$$

The associated friction force is given by

$$\bar{F}_{f23} = \mu s_{2R}F_{23}\bar{n}_{N\lambda 2} \tag{D-146}$$

where, according to eq G-49 of ref 5

$$\bar{n}_{N\lambda 2} = -\sin\lambda_2\bar{i} + \cos\lambda_2\bar{j} \tag{D-147}$$

The signum function s_{2R} is defined with the help of eq F-47 of appendix F

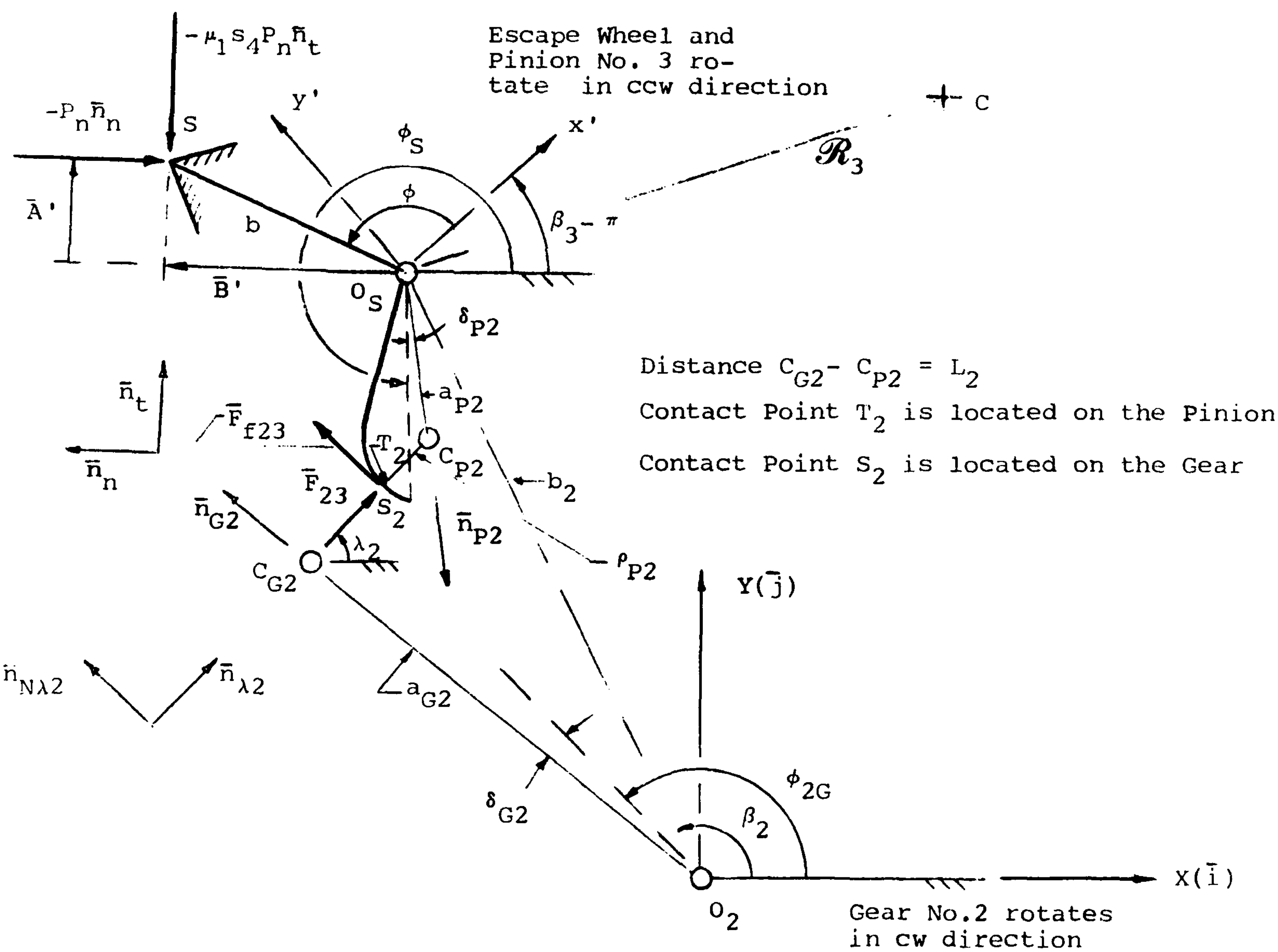


Figure D-5a. Top view of escape wheel and pinion no. 3 in entrance coupled motion. Round-on-round contact of mesh no. 2

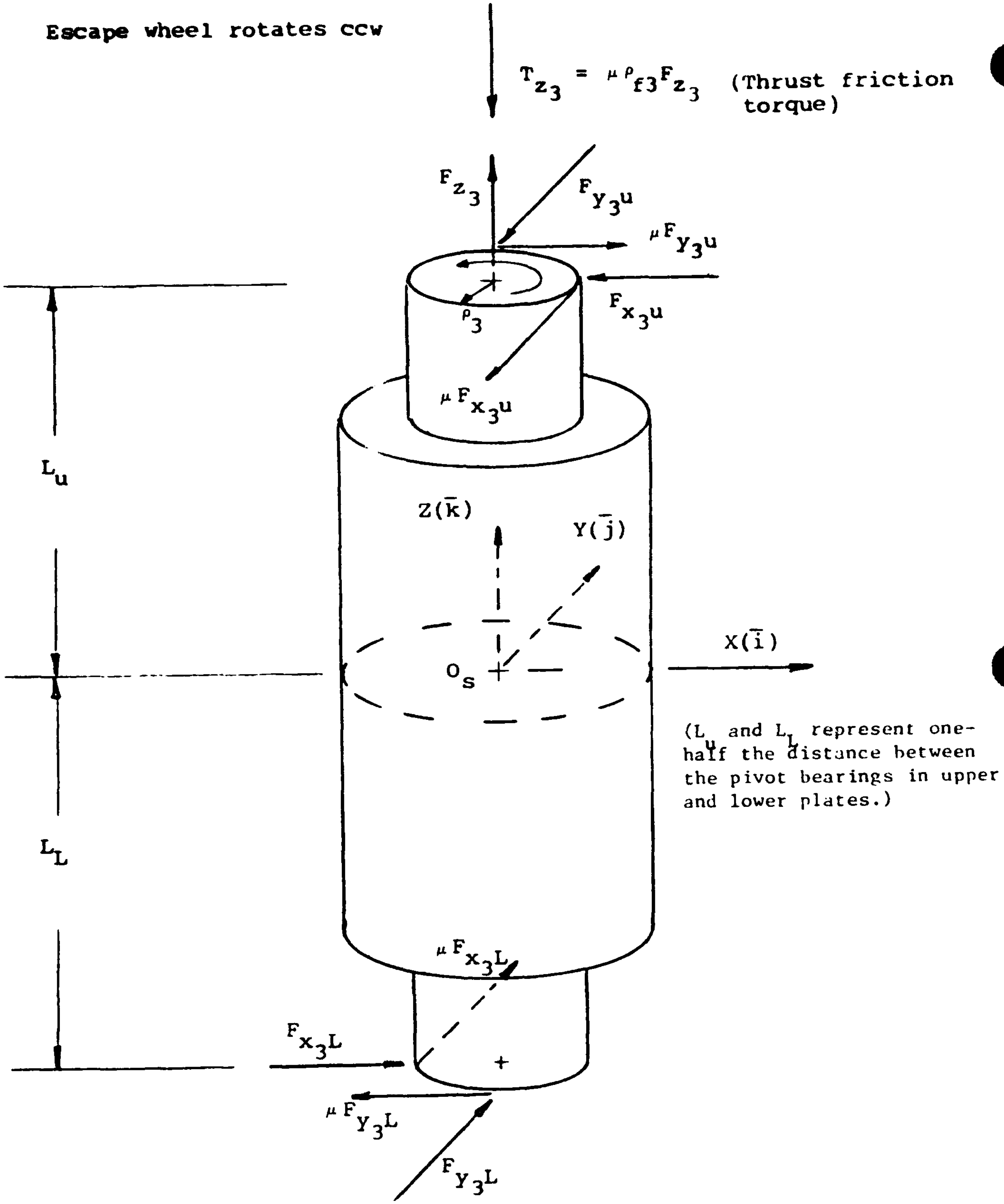


Figure D-5b. Escape wheel and pinion no. 3 in entrance coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots. (Not influenced by type of mesh contact.)

$$S_{2R} = \frac{V_{S_2/T_{2_R}}}{\left|V_{S_2/T_{2_R}}\right|} \tag{D-148}$$

The force equations for the escape wheel in coupled motion are generally obtained from Newton's law

$$\Sigma\bar{F} = m_3\bar{A}_{O_s/ground} \tag{D-149}$$

where

$\Sigma\bar{F}$ = sum of pivot forces as well as contact forces P_n and F_{23} and their associated friction forces

m_3 = mass of escape wheel and pinion no. 3

$\bar{A}_{O_s/ground}$ = acceleration of escape wheel center of mass, which lies on axis of rotation, with respect to ground. Therefore

$$\bar{A}_{O_s/ground} = \bar{A}_{O_s/C} + \bar{A}_{C/ground} \tag{D-150}$$

In the above, $\bar{A}_{C/ground}$, the acceleration of the fuze geometric center C with respect to the ground is given in terms of the X-Y-Z system by equation C-4 of appendix C. The acceleration of the escape wheel center of mass with respect to the above point C, i.e., $A_{O_s/C}$, becomes

$$\bar{A}_{O_s/C} = \bar{\omega}_x \times (\bar{\omega}_x \times \Re_3\bar{n}_3) + \dot{\bar{\omega}} \times \Re_3\bar{n}_3 \tag{D-151}$$

where

$$\bar{n}_3 = \cos\gamma_3\bar{i} + \sin\gamma_3\bar{j} \tag{D-152}$$

Substitution of

$$\bar{\omega} = \omega_x\bar{i} + w_y\bar{j} + w_z\bar{k} \tag{D-153}$$

according to equation A-1 and

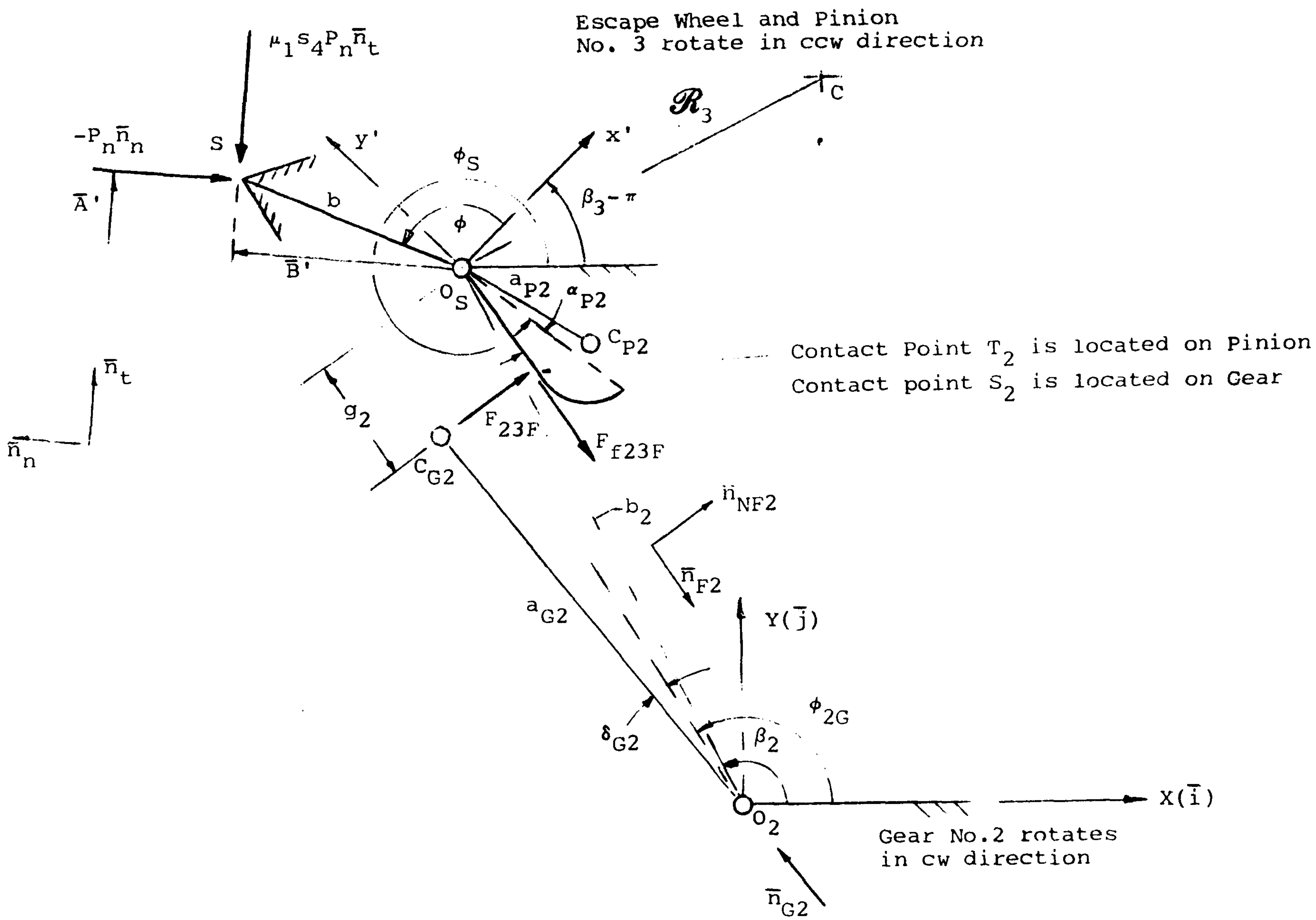


Figure D-6a. Top view of escape wheel and pinion no. 3 in entrance coupled motion. Round-on-flat contact of mesh no. 2

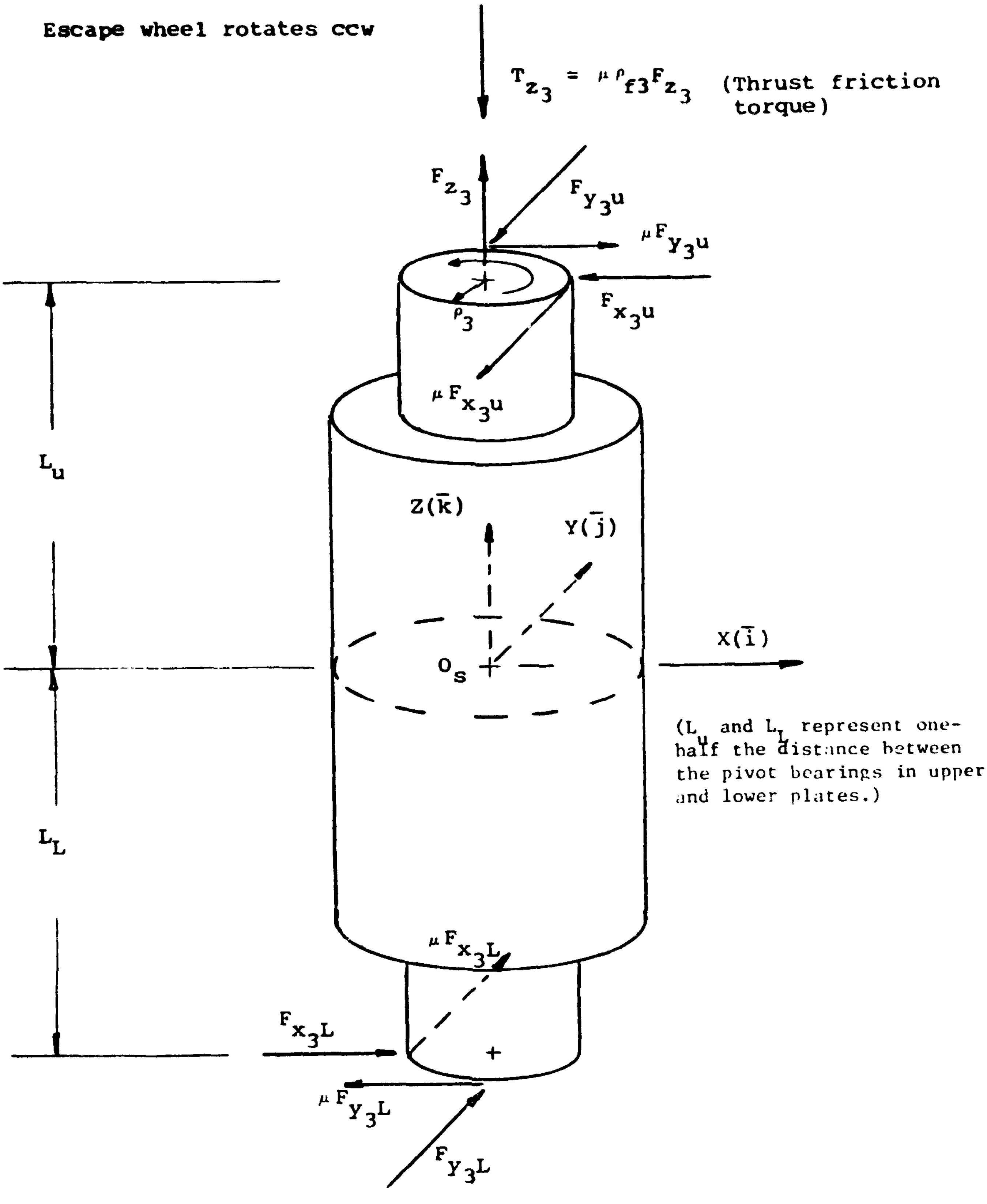


Figure D-6b. Escape wheel and pinion no. 3 in entrance coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots. (Same as figure D-5b. Not influenced by type of mesh contact.)

$$\bar{\dot{\omega}} = \dot{\omega}_x\bar{i} + \dot{\omega}_y\bar{j} + \dot{\omega}_z\bar{k} \tag{D-154}$$

according to equation A-5, with

$$\Re_{3x} = \Re_3\cos\gamma_3 \tag{D-155}$$

and

$$\Re_{3x} = \Re_3\sin\gamma_3 \tag{D-156}$$

results in

$$\bar{A}_{O_s/C} = J_x\bar{i} + J_y\bar{j} + J_z\bar{k} \tag{D-157}$$

where

$$J_x = \omega_x\omega_y\Re_{3y} - (\omega_y{}^2 + \omega_z{}^2)\Re_{3x} - \dot{\omega}_z\Re_{3y} \tag{D-158}$$

$$J_y = \omega_x\omega_y\Re_{3x} - (\omega_x{}^2 + \omega_y{}^2)\Re_{3x} + \dot{\omega}_z\Re_{3y} \tag{D-159}$$

$$J_z = (\omega_x\Re_{3x} + \omega_y\Re_{3y})\,\omega_z + \dot{\omega}_x\Re_{3y} - \dot{\omega}_y\Re_{3x} \tag{D-160}$$

Equation D-157 is now substituted together with equation C-3 into D-150

$$\bar{A}_{O_s/\text{ground}} = N_x\bar{i} + N_y\bar{j} + N_z\bar{k} \tag{D-161}$$

where

$$N_x = G_x + J_x \tag{D-162}$$

$$N_y = G_y + J_y \tag{D-163}$$

$$N_z = G_z + J_z \tag{D-164}$$

The vectorial force equation is now obtained with the help of figures D-5a and D-5b, and equation D-149

$$-P_n\bar{n}_n - \mu_1 s_4 P_n \bar{n}_t + F_{23}\bar{n}_{\lambda 2} + \mu s_{2R} F_{23} \bar{n}_{N\lambda 2} + F_{z3}\bar{k} - F_{x3u}\bar{i} - F_{y3u}\bar{j} - \mu F_{x3u}\bar{j}$$

$$+ \mu F_{y3u}\bar{i} + F_{x3L}\bar{i} + F_{y3L}\bar{j} + \mu F_{x3L}\bar{j} - \mu F_{y3L}\bar{i} = \left(N_x\bar{i} + N_y\bar{j} + N_z\bar{k}\right) m_3 \qquad \text{(D-165)}$$

Substitution of the appropriate unit vectors, according to equations D-143 and D-146

$$-P_n\left[\sin\left(\psi + \alpha + \beta_3\right)\bar{i} - \cos\left(\psi + \alpha + \beta_3\right)\bar{j}\right] - \mu_1 s_4 P_n\left[-\cos\left(\psi + \alpha + \beta_3\right)\bar{i}\right.$$

$$\left. - \sin\left(\psi + \alpha + \beta_3\right)\bar{j}\right] + F_{23}[\cos\lambda_2\bar{i} + \sin\lambda_2\bar{j}] + \mu s_{2R} F_{23}\left[-\sin\lambda_2\bar{i} + \cos\lambda_2\bar{j}\right]$$

$$+ F_{23}\bar{k} - F_{x3u}\bar{i} - F_{y3u}\bar{j} - \mu F_{x3u}\bar{j} + F_{y3u}\bar{i} + F_{x3L}\bar{i} + F_{y3L}\bar{j} + \mu F_{x3L}\bar{j} - \mu F_{y3L}\bar{i}$$

$$= \left(N_x\bar{i} + N_y\bar{j} + N_z\bar{k}\right) m_3$$

This leads to the following force component expressions

$$- P_n \sin(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \cos(\psi + \alpha + \beta_3) + F_{23}\cos\lambda_2$$

$$- \mu s_{2r} F_{23} \sin\lambda_2 - F_{x3u} + \mu F_{y3u} + F_{x3L} - \mu F_{y3L} = N_x m_3 \qquad \text{(D-166)}$$

as well as

$$P_n \cos(\psi + \alpha + \beta_3) + P_n \mu_1 s_4 \sin(\psi + \alpha + \beta_3) + F_{23}\sin\lambda_2$$

$$+ \mu s_{2r} F_{23} \cos\lambda_2 - F_{y3u} - \mu F_{x3u} + F_{y3L} + \mu F_{x3L} = N_y m_3 \qquad \text{(D-167)}$$

and

$$F_{23} = N_z m_3 \qquad \text{(D-168)}$$

Moment Equations for Escape Wheel and Pinion No. 3 with Mesh in Round-on Round Contact

Since the escape wheel and pinion no. 3 represents a symmetrical body, its moment equation may be expressed in terms of the projectile-fixed X-Y-Z system according to equation B-13 of appendix B. Adaptation of this expression to the escape wheel system furnishes

$$\overline{M}_{O_s} = \left[I_{xs}\dot{\omega}_x + I_{zs}\omega_y\left(\omega_z + \dot{\phi}\right) - I_{ys}\omega_y\omega_z\right]\bar{i} + \left[I_{ys}\dot{\omega}_y + I_{xs}\omega_x\omega_z - I_{zs}\omega_x\left(\omega_z + \dot{\phi}\right)\right]\bar{j} + I_{zs}\left(\dot{\omega}_z + \ddot{\phi}\right)\bar{k} \quad \text{(D-169)}$$

The moment sum $\overline{M}_{O_s}$ about point O_s is now found with the help of the free body diagrams of figures D-5a and D-5b (also refs 1 and 2).

$$M_{O_s} = -P_n\left(A_1' - B_1'\mu_1 s_4\right)\bar{k} - \mu\rho_{f3}F_{z3}\bar{k} + \left(a_{p2}\bar{n}_{p2} - \rho_{p2}\bar{n}_{\lambda 2}\right) \times \left(F_{23}\bar{n}_{\lambda 2} + \mu s_{2R}F_{23}\bar{n}_{N\lambda 2}\right) + \left(L_u\bar{k} + \rho_3\bar{j}\right) \times \left(-F_{y3u}\bar{j} + \mu F_{y3u}\bar{i}\right) + \left(L_u\bar{k} + \rho_3\bar{i}\right) \times \left(-F_{x3u}\bar{i} - \mu F_{x3u}\bar{j}\right) + \left(-L_L\bar{k} - \rho_3\bar{j}\right) \times \left(F_{y3L}\bar{j} - \mu F_{y3L}\bar{i}\right) + \left(-L_L\bar{k} - \rho_3\bar{i}\right) \times \left(F_{x3L}\bar{i} + \mu F_{x3L}\bar{j}\right) \quad \text{(D-170)}$$

The term $-\mu\rho_{f3}F_{z3}$ represents the thrust friction moment due to force F_{z3} (eq D-168). The term ρ_{f3} stands for the thrust friction radius of the escape wheel pivot. Further, the unit (vector $\bar{n}_{pz}$) is given by equation G-50 of reference 5. The subscript s is now used with the angle ϕ.

Then, with equation D-145 and D-147 and

$$\bar{n}_{p2} = \cos\left(\phi_s + \delta_{p2}\right)\bar{i} + \sin\left(\phi_s + \delta_{p2}\right)\bar{j} \quad \text{(D-171)}$$

equation D-170 becomes

$$M_{O_s} = -P_n\left(A_1' - B_1'\mu_1 s_4\right)\bar{k} - \mu\rho_{f3}F_{z3}\bar{k} + a_{p2}F_{23}\left(\bar{n}_{p2} \times \bar{n}_{\lambda 2}\right) + a_{p2}\mu s_{2R}F_{23}\left(\bar{n}_{p2} \times \bar{n}_{N\lambda 2}\right) - \rho_{p2}u s_{2R}F_{23}\left(\bar{n}_{\lambda 2} \times \bar{n}_{N\lambda 2}\right) + \left(L_u\bar{k} + \rho_3\bar{j}\right) \times \left(-F_{y3u}\bar{j} + \mu F_{y3u}\bar{i}\right) + \left(L_u\bar{k} + \rho_3\bar{i}\right) \times \left(-F_{x3u}\bar{i} - \mu F_{x3u}\bar{j}\right) + \left(-L_L\bar{k} - \rho_3\bar{j}\right) \times \left(F_{y3L}\bar{j} - \mu F_{y3L}\bar{i}\right) + \left(-L_L\bar{k} + \rho_3\bar{i}\right) \times \left(F_{x3L}\bar{i} + \mu F_{x3L}\bar{j}\right)$$

with

$$\bar{n}_{p2} \times \bar{n}_{\lambda 2} = \left[\cos\left(\phi_s + \delta_{p2}\right)\bar{i} + \sin\left(\phi_s + \delta_{p2}\right)\bar{j}\right] \times \left[\cos\lambda_2\bar{i} + \sin\lambda_2\bar{j}\right]$$

$$= \left[\cos\left(\phi_s + \delta_{p2}\right)\sin\lambda_2 - \sin\left(\phi_s + \delta_{p2}\right)\cos\lambda_2\right]\bar{k} = \sin\left(\lambda_2 - \phi_s - \delta_{p2}\right)\bar{k}$$

$$\bar{n}_{p2} \times \bar{n}_{N\lambda 2} = \left[\cos\left(\phi_s + \delta_{p2}\right)\bar{i} + \sin\left(\phi_s + \delta_{p2}\right)\bar{j}\right] \times \left[-\sin\lambda_2\bar{i} + \cos\lambda_2\bar{j}\right]$$

$$= \cos\left(\phi_s + \delta_{p2}\right)\cos\lambda_2 + \sin\left(\phi_s + \delta_{p2}\right)\sin\lambda_2 = \cos\left(\lambda_2 - \phi_s - \delta_{p2}\right)\bar{k}$$

$$\bar{n}_{\lambda 2} \times \bar{n}_{N\lambda 2} = \bar{k}$$

Subsitu:ion furnishes

$$\bar{M}_{O_s} = -P_n\left(A_1' - B_1'\mu_1 s_4\right)\bar{k} - \mu\rho_{f3}F_{z3}\bar{k} + a_{p2}F_{23}\sin\left(\lambda_2 - \phi_s - \delta_{p2}\right)\bar{k}$$

$$+ a_{p2}\mu s_{2R}F_{23}\cos\left(\lambda_2 - \phi_s - \delta_{p2}\right)\bar{k} - \rho_{p2}\mu s_{2R}F_{23}\bar{k} - \rho_3\mu F_{y3u}\bar{k} - \rho_3\mu F_{x3u}\bar{k}$$

$$- \rho_3\mu F_{y3L}\bar{k} - \rho_3\mu F_{x3L}\bar{k} + \left[L_uF_{y3u} + L_u\mu F_{x3u} + L_LF_{y3L} + L_L\mu F_{x3L}\right]\bar{i}$$

$$+ \left[L_u\mu F_{y3u} - L_uF_{x3u} + L_L\mu F_{y3L} - L_LF_{x3L}\right]\bar{j}$$

or

$$\bar{M}_{O_s} = \left[L_uF_{y3u} + L_u\mu F_{x3u} + L_LF_{y3L} + L_L\mu F_{x3L}\right]\bar{i} + \left[L_u\mu F_{y3u} - L_uF_{x3u}\right.$$

$$\left. + L_L\mu F_{y3L} - L_LF_{x3L}\right]\bar{j} + \left[-P_n\left(A_1' - B_1'\mu_1 s_4\right) + a_{p2}F_{23}\left[\sin\left(\lambda_2 - \phi_s - \delta_{p2}\right)\right.\right.$$

$$\left.\left. + \mu s_{2R}\cos\left(\lambda_2 - \phi_s - \delta_{p2}\right)\right] - \mu s_{2R}\rho_{p2}F_{23} - \mu\rho_{f3}F_{z3} - \rho_3\mu F_{y3u} - \rho_3\mu F_{x3u}\right.$$

$$\left. - \rho_3\mu F_{y3L} - \rho_3\mu F_{x3L}\right]\bar{k} \qquad \text{(D-172)}$$

Substitution of equatior 72 into equation D-169 leads to the following moment component expressions

$$L_u\mu F_{x3u} + L_u F_{y3u} + L_L\mu F_{x3L} + L_L F_{y3L}$$

$$= I_{xs}\dot{\omega}_x + I_{zs}\omega_y\left(\omega_z + \dot{\phi}\right) - I_{ys}\omega_y\omega_z \qquad \text{(D-173)}$$

$$- L_u F_{x3u} + L_u\mu F_{y3u} - L_L F_{x3L} + L_L\mu F_{y3L}$$

$$= I_{ys}\dot{\omega}_y + I_{xs}\omega_x\omega_z - I_{zs}\omega_x\left(\omega_s + \right. \qquad \text{(D-174)}$$

$$- P_n\left(A_1' - B_1'\mu_1 s_4\right) + a_{p2}F_{23}\left[\sin\left(\lambda_2 - \phi_s - \delta_{p2}\right) + \mu s_{2r}\cos\left(\lambda_2 - \phi_s - \delta_{p2}\right)\right]$$

$$- \mu s_{2r}\rho_{p2}F_{23} - \mu\rho_{f3}F_{z3} - \mu\rho_3\left[F_{x3u} + F_{y3u} + F_{x3L} + F_{y3L}\right]$$

$$= I_{zs}\left(\dot{\omega}_z + \ddot{\phi}\right) \qquad \text{(D-175)}$$

Simplification of Force and Moment Equations and Determination of Escape Wheel Pivot Forces

To solve for the pivot forces F_{x3u}, F_{y3u}, F_{x3L}, and F_{y3L}, the X and Y components of the force and moment equations must be rewritten in an appropriate form.

<u>X-Component of Force Equation</u>

Equation D-166 becomes

$$F_{x3u} = -\mu F_{y3u} - F_{x3L} + \mu F_{y3L} = P_n A_{33R} + F_{23}A_{34R} + A_{35R} \qquad \text{(D-176)}$$

where

$$A_{33R} = \mu_1 s_4 \cos\left(\psi + \alpha + \beta_3\right) - \sin\left(\psi + \alpha + \beta_3\right) \qquad \text{(D-177)}$$

$$A_{34R} = \cos\lambda_2 - \mu s_{2R}\sin\lambda_2 \qquad \text{(D-178)}$$

$$A_{35R} = - N_x m_3 \qquad \text{(D-179)}$$

Y-Component of Force Equation

Equation D-167 becomes

$$\mu F_{x3u} + F_{y3u} - \mu F_{x3L} - F_{y3L} = P_n A_{36R} + F_{23} A_{37R} + A_{38R} \tag{D-180}$$

where

$$A_{36R} = \cos\left(\psi + \alpha + \beta_3\right) + \mu_1 s_4 \sin\left(\psi + \alpha + \beta_3\right) \tag{D-181}$$

$$A_{37R} = \sin\lambda_2 + \mu s_{2R} \cos\lambda_2 \tag{D-182}$$

$$A_{38R} = - N_y m_3 \tag{D-183}$$

Z-Component of Force Equation

Equation D-168 cannot be further simplified.

X-Component of Moment Equation

Equation D-173 becomes

$$\mu L_u F_{x3u} + L_u F_{y3u} + \mu L_L F_{x3L} + L_L F_{y3L} = A_{39R} + A_{40R}\dot{\phi} \tag{D-184}$$

where

$$A_{39R} = I_{xs}\dot{\omega}_x + \omega_y \omega_z \left(I_{zs} - I_{ys}\right) \tag{D-185}$$

$$A_{40R} = I_{zs}\omega_y \tag{D-186}$$

Y-Component of Moment Equation

Equation D-174 becomes

$$- L_u F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L} = A_{41R} + A_{41R}\dot{\phi} \tag{D-187}$$

where

$$A_{41R} = I_{ys}\dot{\omega}_y + \omega_x \omega_z (I_{xs} - I_{zs}) \tag{D-188}$$

$$A_{42R} = - I_{zs}\omega_x \tag{D-189}$$

Z-Component of Moment Equation

For present purposes equation D-175 remains as it is.

Solution of Escape Wheel Pivot Forces. To derive expressions for the escape wheel pivot forces, equations D-176, D-180, D-184, and D-187 must be solved simultaneously. To obtain the same general form as in equation D-67, equations D-186 and D-180 are multiplied by (-1). The resulting form may then use the solution to equation D-167. Note that A_{11} in equation D-67 is now replaced by μ. Then

$$\begin{bmatrix} -1 & \mu & 1 & -\mu \\ -\mu & -1 & \mu & 1 \\ \mu L_u & L_u & \mu L_L & L_L \\ -L_u & \mu L_u & -L_L & \mu L_L \end{bmatrix} \begin{bmatrix} F_{x3u} \\ F_{y3u} \\ F_{x3L} \\ F_{y3L} \end{bmatrix} = \begin{bmatrix} B_{s1r} \\ B_{s2r} \\ B_{s3r} \\ B_{s4r} \end{bmatrix} \quad \text{(D-190)}$$

where now

$$B_{s1r} = -[P_n A_{33R} + F_{23} A_{34R} + A_{35R}] \quad \text{(D-191)}$$

$$B_{s2r} = [P_n A_{36R} + F_{23} A_{37R} + A_{38R}] \quad \text{(D-192)}$$

$$B_{s3r} = A_{39R} + A_{40R}\dot{\phi} \quad \text{(D-193)}$$

$$B_{s4r} = A_{41R} + A_{42R}\dot{\phi} \quad \text{(D-194)}$$

Evaluation of the Coefficient Determinant D

The solution for the coefficient determinant D of equation D-190 is identical to equation D-72. With A_{11} now equal to μ, the following parallel to equation D-75 is obtained

$$D = [(L_u + L_L)(1 + \mu^2)]^2 \quad \text{(D-195)}$$

Evaluation of Pivot Force $\tilde{F}_{x3u}$

The pivot force F_{x3u} is obtained from

$$F_{x3u} = \frac{D_{F_{x3u}}}{D} \quad \text{(D-196)}$$

where

$$D_{F_{x3u}} = \begin{vmatrix} B_{x1r} & \mu & 1 & -\mu \\ B_{s2r} & -1 & \mu & 1 \\ B_{s3r} & L_u & \mu L_L & L_L \\ B_{s4r} & \mu L_u & -L_L & \mu L_L \end{vmatrix} \tag{D-197}$$

If μ is substituted for A_{11} in equation D-77, the identical form as above is obtained and the solution of equation D-80 can be adapted

$$D_{F_{x3u}} = \left(1 + \mu^2\right)\left(L_u + L_L\right)\left[-L_L B_{s1r} - \mu L_L B_{s2r} + \mu B_{s3r} - B_{s4r}\right] \tag{D-198}$$

Now equations D-191 to D-194 are substituted into the above expression and the coefficients of similar terms are collected. In order to get conservative pivot and pivot friction forces, the latter terms are made absolute. Finally, the tilded force $\tilde{F}_{x3u}$ is obtained from the appropriate change of equation D-196

$$\tilde{F}_{x3u} = \frac{\tilde{D}_{F_{x3u}}}{D} = \frac{1}{\left(L_u + L_L\right)\left(1 + \mu^2\right)}\left[C_{21R} + C_{22R}P_n + C_{23R}F_{23} + C_{24R}\dot{\phi}\right] \tag{D-199}$$

where

$$C_{21R} = \left|L_L A_{35R} - A_{41R} + \mu\left(L_L A_{38R} + A_{39R}\right)\right| \tag{D-200}$$

$$C_{22R} = \left|L_L\left(A_{33R} + \mu A_{36R}\right)\right| \tag{D-201}$$

$$C_{23R} = \left|L_L\left(A_{34R} + \mu A_{37R}\right)\right| \tag{D-202}$$

$$C_{24R} = \left|\mu A_{40R} - A_{42R}\right| \tag{D-203}$$

<u>Evaluation of Pivot Force</u> $\tilde{F}_{y3u}$

The pivot force F_{y3u} is obtained from

$$F_{y3u} = \frac{D_{D_{y3u}}}{D} \tag{D-204}$$

where

$$D_{F_{y3u}} = \begin{vmatrix} -1 & B_{s1r} & 1 & -\mu \\ -\mu & B_{s2r} & \mu & 1 \\ \mu L_u & B_{s3r} & \mu L_L & L_L \\ -L_u & B_{s4r} & -L_L & \mu L_L \end{vmatrix} \quad \text{(D-205)}$$

Since the form of the above is the same as that of the determinant of equation D-89, equation D-90, which represents the solution of the latter, may be adapted as follows

$$D_{F_{x3u}} = \left(1 + \mu^2\right)\left(L_u + L_L\right)\left[-L_L B_{s1r} - \mu L_L B_{s2r} + \mu B_{s3r} - B_{s4r}\right] \quad \text{(D-206)}$$

Again, substitue the B_{s1r} terms of equations D-191 to D-194, collect the coefficients of similar terms, and make the result absolute. The tilded pivot force $\widetilde{F}_{y3u}$ then becomes parallel to equation D-199

$$\widetilde{F}_{y3u} = \frac{\widetilde{D}_{F_{y3u}}}{D} = \frac{1}{\left(L_u + L_L\right)\left(1 + \mu^2\right)}\left[C_{25R} + C_{26R}P_n + C_{27R}F_{23} + C_{28R}\dot{\phi}\right] \quad \text{(D-207)}$$

where

$$C_{25R} = \left|L_L A_{38R} + A_{39R} + \mu\left(A_{41R} - L_L A_{35R}\right)\right| \quad \text{(D-208)}$$

$$C_{26R} = \left|L_L\left(A_{36R} - \mu A_{33R}\right)\right| \quad \text{(D-209)}$$

$$C_{27R} = \left|L_L\left(A_{37R} - \mu A_{34R}\right)\right| \quad \text{(D-210)}$$

$$C_{28R} = \left|A_{40R} + \mu A_{42R}\right| \quad \text{(D-211)}$$

<u>Evaluation of Pivot Force</u> $\widetilde{F}_{x3L}$

The pivot force F_{x3L} is obtained from

$$F_{x3L} = \frac{D_{F_{x3L}}}{D} \quad \text{(D-212)}$$

where

$$D_{F_{x3L}} = \begin{vmatrix} -1 & \mu & B_{s1r} & -\mu \\ -\mu & -1 & B_{s2r} & 1 \\ \mu L_u & L_u & B_{s3r} & L_L \\ -L_u & \mu L_u & B_{s4r} & \mu L_L \end{vmatrix} \tag{D-213}$$

Since the form of the above is the same as that of equation D-98, equation D-100 may be adapted

$$D_{F_{x3L}} = (L_u + L_L)\left(1 + \mu^2\right)\left[L_u B_{s1r} + \mu L_u B_{s2r} + \mu B_{s3r} - B_{s4r}\right] \tag{D-214}$$

Again, the B_{s1r} terms are substituted according to equations D-191 to D-194 and the requisite work obtains the tilded determinant $\widetilde{D}_{F_{x3L}}$. Then

$$\widetilde{F}_{x3L} = \frac{\widetilde{D}_{F_{x3L}}}{D} = \frac{1}{(L_u + L_L)\left(1 + \mu^2\right)}\left[C_{29R} + C_{30R}P_n + C_{31R}F_{23} + C_{32R}\dot{\phi}\right] \tag{D-215}$$

where

$$C_{29R} = |\mu(A_{39R} - L_u A_{38R}) - L_u A_{35R} - A_{41R}| \tag{D-216}$$

$$C_{30R} = |L_u(A_{33R} + \mu A_{36R})| \tag{D-217}$$

$$C_{31R} = |L_u(A_{34R} + \mu A_{37R})| \tag{D-218}$$

$$C_{32R} = |\mu A_{40R} - A_{42R}| \tag{D-219}$$

Evaluation of Pivot Force $\widetilde{F}_{y3L}$

The pivot force F_{y3L} is obtained from

$$F_{y3L} = \frac{D_{F_{y3L}}}{D} \tag{D-220}$$

where

$$D_{Fy3L} = \begin{vmatrix} -1 & \mu & 1 & B_{s1r} \\ -\mu & -1 & \mu & B_{s2r} \\ \mu L_u & L_u & \mu L_L & B_{s3r} \\ -L_u & \mu L_u & -L_L & B_{s4r} \end{vmatrix} \qquad \text{(D-221)}$$

Since the form of the above is the same as that of the determinant of equation D-108, equation D-110 may be adapted to the present situation, therefore

$$D_{Fy3L} = (L_u + L_L)(1 + \mu^2)[-\mu L_u B_{s1r} + L_u B_{s2r} + B_{s3r} + \mu B_{s4r}] \qquad \text{(D-222)}$$

The B_{s1r} terms are now substituted according to equations D-191 to D-194, terms are collected and the tilded pivot force is defined

$$\tilde{F}_{y3L} = \frac{\tilde{D}_{Fy3L}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)}\left[C_{33R} + C_{34R}P_n + C_{35R}F_{23} + C_{36R}\dot{\phi}\right] \qquad \text{(D-223)}$$

where

$$C_{33R} = |\mu(A_{41R} + L_u A_{35R}) + A_{39R} - L_u A_{38R}| \qquad \text{(D-224)}$$

$$C_{34R} = |L_u(\mu A_{33R} - A_{36R})| \qquad \text{(D-225)}$$

$$C_{35R} = |L_u(\mu A_{34R} - A_{37R})| \qquad \text{(D-226)}$$

$$C_{36R} = |A_{40R} - \mu A_{42R}| \qquad \text{(D-227)}$$

Determiniation of Contact Force P_n in Terms of Escape Wheel Parameters (Round-on-Round Contact)

Substitution of Conservative (Tilded) Pivot Forces into the z-Component of the Moment Equation. *Again, let the sum of the tilded pivot forces be first determined.* Subsequently, this expression is substituted into the moment equation D-175. Then

$$\tilde{F}_{x3u} + \tilde{F}_{y3u} + \tilde{F}_{x3L} + \tilde{F}_{y3L} = A_{43R} + A_{44R}P_n + A_{45R}F_{23} + A_{46R}\dot{\phi} \qquad \text{(D-228)}$$

where

$$L_T = L_U + L_L \qquad \text{(D-229)}$$

$$A_{43R} = \frac{C_{21R} + C_{25R} + C_{29R} + C_{33R}}{L_T(1+\mu^2)} \qquad \text{(D-230)}$$

$$A_{44R} = \frac{C_{22R} + C_{26R} + C_{30R} + C_{34R}}{L_T(1+\mu^2)} \qquad \text{(D-231)}$$

$$A_{45R} = \frac{C_{23R} + C_{27R} + C_{31R} + C_{35R}}{L_T(1+\mu^2)} \qquad \text{(D-232)}$$

$$A_{46R} = \frac{C_{24R} + C_{28R} + C_{32R} + C_{36R}}{L_T(1+\mu^2)} \qquad \text{(D-233)}$$

Equation D-228 is now substituted into equation D175. Further, F_{z3} of equation D-168 is made conservative, i.e.

$$\tilde{F}_{z3} = A_{47} = |N_z m_3| \qquad \text{(D-234)}$$

Equation D-175 then becomes

$$-P_n(A_1' - B_1\mu_1 s_4) + F_{23}\, a_{p2}\left(\sin(\lambda_2 - \phi_s - \delta_{p2}) + \mu s_{2R}\cos(\lambda_2 - \phi_s - \delta_{p2})\right)$$

$$\mu s_{2R}\rho_{P2}F_{23} - \mu\rho_{f3}A_{47} - \mu\rho_3\left[A_{43R} + A_{44R}P_n + A_{45R}F_{23} + A_{46R}\dot{\phi}\right]$$

$$= I_{zs}\dot{\omega}_z + I_{zs}\ddot{\phi} \qquad \text{(D-235)}$$

The above expression must now be solved for P_n. Before this is possible consider the sign of the friction moment component

$$-\mu\rho_3 A_{46R}\dot{\phi} \tag{D-236}$$

Since a reversal of gear train motion after impact will again be expressed by letting μ become negative, as described originally in appendix E of reference 4, equation D-236 is modified to read

$$-\mu\rho_3 A_{46R}\frac{\dot{\phi}^2}{|\dot{\phi}|} \tag{D-237}$$

In this way, the sign of μ alone decides the direction of this friction torque component. P_n is then obtained from equation D-235

$$P_n\left[-A_1' + B_1'\mu_1 s_4 - \mu\rho_3 A_{44R}\right] + F_{23}\left[a_{P2}\left(\sin\left(\lambda_2 - \phi_s - \delta_{P2}\right)\right.\right.$$

$$\left.\left.+ \mu s_{2R}\cos\left(\lambda_2 - \phi_s - \delta_{P2}\right)\right) - \mu s_{2R}\rho_{P2} - \mu\rho_3 A_{45R}\right] - \mu\rho_3 A_{46R}\frac{\dot{\phi}^2}{|\dot{\phi}|}$$

$$- \mu\left[\rho_{f3}A_{47} + \rho_3 A_{43R}\right] = I_{zs}\ddot{\phi} + I_{zs}\dot{\omega}_z \tag{D-238}$$

Then

$$P_n = \frac{I_{zs}\ddot{\phi} + A_{48R}\dot{\phi}^2 + F_{23}A_{49R} + A_{50R}}{A_{51R}} \tag{D-239}$$

where

$$A_{48R} = \frac{\mu\rho_3 A_{46R}}{|\dot{\phi}|} \tag{D-240}$$

$$A_{49R} = \mu\left(s_{2R}\rho_{P2} + \rho_3 A_{45R}\right) - a_{P2}\left[\sin\left(\lambda_2 - \phi_s - \delta_{P2}\right)\right.$$

$$\left.+ \mu s_{2R}\cos\left(\lambda_2 - \phi_s - \delta_{P2}\right)\right] \tag{D-241}$$

$$A_{50R} = I_{zs}\dot{\omega}_z + \mu\left[\rho_{f3}A_{47} + \rho_3 A_{43R}\right] \qquad \text{(D-242)}$$

$$A_{51R} = B_1'\mu_1 s_4 - A_1' - \mu\rho_3 A_{44R} \qquad \text{(D-243)}$$

Combined Entrance Coupled Motion Differential Equation with Mesh 2 in Round-on-Round Contact

Equations D-140 and D-239 are now set equal to each other. This furnishes the following combined coupled motion differential equation for the escapement under entrance conditions and with mesh 2 in round-on-round contact.

$$\left[A_{51R}I_{PR}U - A_{29}I_{zs}\right]\ddot{\phi} + \left[A_{51R}\left(A_{32}U^2 + I_{PR}V\right) - A_{29}A_{48R}\right]\dot{\phi}^2$$

$$+ A_{51R}A_{31}U\dot{\phi} = F_{23}A_{29}A_{49R} + A_{29}A_{50R} - A_{51R}\left(A_9 + A_{30}\right)$$

$$+ A_{51R}m_p r_{cp}\left(K_x \sin\beta - K_y \cos\beta\right) \qquad \text{(D-244)}$$

Force Equations for Escape Wheel and Pinion No. 3 with Mesh 2 in Round-on-Flat Contact (see reference 5 for clock tooth force analysis background)

The action of the contact forces $\overline{P}_n$ and $\overline{F}_{23F}$, together with their associated friction forces, on escape wheel and pinion no. 3, when mesh no. 2 is in round-on-flat contact is shown in figure D-6a. Figure D-6b is identical to figure D-5b, which showed a free body diagram of the escape wheel pivot shaft. As for the round-on-round contact, equations (D-141) to (D-144) for the unit vectors $\bar{i}'$, $\bar{j}'$, $\bar{n}_t$, and $\bar{n}_n$ are applicable.

The round-on-flat contact force $\overline{F}_{23F}$ has the direction of the unit vector $\bar{n}_{NF2}$, so that

$$\overline{F}_{23F} = F_{23F}\bar{n}_{NF2} \qquad \text{(D-245a)}$$

where

$$\bar{n}_{NF2} = -\sin\left(\phi_s - \alpha_{P2}\right)\bar{i} + \cos\left(\phi_s - \alpha_{P2}\right)\bar{j} \qquad \text{(D-245b)}$$

(eq G-65, ref 5).

The associated friction force is given by

$$\overline{F}_{f23F} = \mu s_{2F} F_{23F}\bar{n}_{F2} \qquad \text{(D-246)}$$

where, according to equation G-64 of reference 5

$$\bar{n}_{F2} = \cos(\phi_s - \alpha_{P2})\,\bar{i} + \sin(\phi_s - \alpha_{P2})\,\bar{j} \tag{D-247}$$

The signum function s_{2F} is defined with the help of equation F-58 of appendix F

$$S_{2F} = \frac{V_{S_2/T_{2_F}}}{\left|V_{S_2/T_{2_F}}\right|} \tag{D-248}$$

The force equation for the escapewheel is again based on equations D-149 and D-161. With the help of figures D-6a and D-6b the following vectorial expression may be written

$$-P_n\bar{n}_n - \mu_1 s_4 P_n \bar{n}_t + F_{23F}\bar{n}_{NF2} + \mu s_{2F} F_{23F}\bar{n}_{F2} + F_{z3}\bar{k} - F_{x3u}\bar{j}$$

$$- F_{y3u}\bar{j} - \mu F_{x3u}\bar{j} + \mu F_{y3u}\bar{i} + F_{x3L}\bar{i} + F_{y3L}\bar{j} + \mu F_{x3L}\bar{j} - \mu F_{y3L}\bar{i}$$

$$= \left(N_x\bar{i} + N_y\bar{j} + N_z\bar{k}\right)m_3 \tag{D-249}$$

Substitution of the appropriate unit vectors according to equations D-143 and D-144 as well as D-245 and D-247 gives

$$-P_n\left[\sin(\psi + \alpha + \beta_3)\,\bar{i} - \cos(\psi + \alpha + \beta_3)\,\bar{j}\right] - \mu_1 s_4 P_n\left[-\cos(\psi + \alpha + \beta_3)\,\bar{i}\right.$$

$$\left. - \sin(\psi + \alpha + \beta_3)\,\bar{j}\right] + F_{23F}\left[-\sin(\phi_s - \alpha_{P2})\,\bar{i} + \cos(\phi_s - \alpha_{P2})\,\bar{j}\right]$$

$$+ \mu s_{2F} F_{23F}\left[\cos(\phi_s - \alpha_{P2})\,\bar{i} + \sin(\phi_s - \alpha_{P2})\,\bar{j}\right] + F_{z3}\bar{k} - F_{x3u}\bar{i} - F_{y3u}\bar{j}$$

$$- \mu F_{x3u}\bar{j} + \mu F_{y3u}\bar{i} + F_{x3L}\bar{i} + F_{y3L}\bar{j} + \mu F_{x3L}\bar{j} - \mu F_{y3L}\bar{i}$$

$$= \left(N_x\bar{i} + N_y\bar{j} + N_z\bar{k}\right)m_3 \tag{D-250}$$

This leads to the following force component equations

$$- P_n \sin(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \cos(\psi + \alpha + \beta_3) - F_{23F}\sin(\phi_s - \alpha_{P2})$$

$$+ \mu s_{2F} F_{23F}\cos(\phi_s - \alpha_{P2}) - F_{x3u} + \mu F_{y3u} + F_{x3L} - \mu F_{y3L} = N_x m_3 \tag{D-251}$$

$$P_n\cos\left(\psi + \alpha + \beta_3\right) + \mu_1 s_4 P_n \sin\left(\psi + \alpha + \beta_3\right) + F_{23F}\cos\left(\phi_s - \alpha_{P2}\right)$$

$$+ \mu s_{2F} F_{23F} \sin\left(\phi_s - \alpha_{P2}\right) - F_{y3u} - \mu F_{x3u} + F_{y3L} + \mu F_{x3L} = N_y m_3 \qquad \text{(D-252)}$$

$$F_{z3} = N_z m_3 \qquad \text{(D-253)}$$

Moment Equations for Escape Wheel and Pinion No. 3 with Mesh 2 in Round-on-Flat Contact

The general moment expression D-169 is also applicable here. The moment sum $\overline{M}_{O_s}$ for the round-on-flat contact must now be found with the help of the free body diagrams D-6a and D-6b

$$\overline{M}_{O_s} = -P_n\left(A_1' - B_1'\mu_1 s_4\right)\overline{k} - \mu\rho_{f3}F_{z3}\overline{k} + g_2\overline{F}n_{F2} \times F_{23F}\overline{F}n_{NF2} + \left(L_u\overline{k} + \rho_3\overline{j}\right)$$

$$\times\left(-F_{y3u}\overline{j} + \mu F_{y3u}\overline{i}\right) + \left(L_u\overline{k} + \rho_3\overline{i}\right) \times \left(-F_{x3u}\overline{i} - \mu F_{x3u}\overline{j}\right) + \left(-L_L\overline{k} - \rho_3\overline{j}\right)$$

$$\times\left(F_{y3L}\overline{j} - \mu F_{y3L}\overline{i}\right) + \left(-L_L\overline{k} - \rho_3\overline{i}\right) \times \left(-F_{x3L}\overline{i} + \mu F_{x3L}\overline{j}\right) \qquad \text{(D-254)}$$

For an explanation of the term $-\mu\rho_{f3}F_{z3}\overline{k}$, see the discussion following equation D-170.

Since

$$\overline{n}_{F2} \times \overline{n}_{NF2} = \overline{k} \qquad \text{(D-255)}$$

equation D-254 may be rewritten as follows

$$\overline{M}_{O_s} = \left[L_u F_{y3u} + L_u \mu F_{x3u} + L_L F_{y3L} + L_L \mu F_{x3L}\right]\overline{i} + \left[L_u \mu F_{y3u} - L_u F_{x3u}\right.$$

$$\left. + L_L \mu F_{y3L} - L_L F_{x3L}\right]\overline{j} + \left[-P_n\left(A_1' - B_1'\mu_1 s_4\right) + g_2 F_{23F} - \mu\rho_{f3}F_{z3} - \rho_3 \mu F_{y3u}\right.$$

$$\left. - \rho_3 \mu F_{x3u} - \rho_3 \mu F_{y3L} - \rho_3 \mu F_{x3L}\right]\overline{k} \qquad \text{(D-256)}$$

Substitution of equation D-255 into equation D-169 leads to the following moment component expressions

$$L_u\mu F_{x3u} + L_u F_{y3u} + L_L\mu F_{x3L} + L_L F_{y3L}$$

$$= I_{xs}\dot{\omega}_x + I_{zs}\omega_y\left(\omega_z + \dot{\phi}\right) - I_{ys}\omega_y\omega_z \qquad \text{(D-257)}$$

$$-L_L F_{x3u} + L_u\mu F_{y3u} - L_L F_{x3L} + L_L\mu F_{y3L}$$

$$= I_{ys}\dot{\omega}_y + I_{xs}\omega_x\omega_z - I_{zs}\omega_x\left(\omega_z + \dot{\phi}\right) \qquad \text{(D-258)}$$

$$-P_n\left(A_1' - B_1'\mu_1 s_4\right) + F_{23F}g_2 - \mu\rho_{f3}F_{z3} - \mu\rho_3\left[F_{x3u} + F_{y3u} + F_{x3L} + F_{y3L}\right]$$

$$= I_{zs}\left(\dot{\omega}_z + \ddot{\phi}\right) \qquad \text{(D-259)}$$

Simplification of Force and Moment Equations and Determination of Escape Wheel Pivot Forces

To solve for the pivot forces F_{x3u}, F_{y3u}, F_{x3L}, and F_{y3L} the X and Y components of the force and moment equations must be rewritten in an appropriate form.

X-Component of Force Equation.

Equation D-251 becomes

$$F_{x3u} - \mu F_{y3u} - F_{x3L} + \mu F_{y3L} = P_n A_{33F} + F_{23}A_{34F} + A_{35F} \qquad \text{(D-260)}$$

where

$$A_{33F} = \mu_1 s_4 \cos\left(\psi + \alpha + \beta_3\right) - \sin\left(\psi + \alpha + \beta_3\right) \qquad \text{(D-261)}$$

$$A_{34F} = -\sin\left(\phi_s - \alpha_{P2}\right) + \mu s_{2F}\cos\left(\phi_s - \alpha_{P2}\right) \qquad \text{(D-262)}$$

$$A_{35F} = -N_x m_3 \qquad \text{(D-263)}$$

Y-Component of Force Equation.

Equation D-252 becomes

$$\mu F_{x3u} + F_{y3u} - \mu F_{x3L} - F_{y3L} = P_n A_{36F} + F_{23} A_{37F} + A_{38F} \tag{D-264}$$

where

$$A_{36F} = \cos(\psi + \alpha + \beta_3) + \mu_1 s_4 \sin(\psi + \alpha + \beta_3) \tag{D-265}$$

$$A_{37F} = \cos(\phi_s - \alpha_{P2}) + \mu s_{2F} \sin(\phi_s - \alpha_{P2}) \tag{D-266}$$

$$A_{38F} = -N_y m_3 \tag{D-267}$$

Z-Component of Force Equation.

Equation D-253 cannot be further simplified.

X-Component of Moment Equation.

Equation D-257 becomes

$$\mu L_u F_{x3u} + L_u F_{y3u} + \mu L_L F_{x3L} + L_L F_{y3L} = A_{39F} + A_{40F} \dot{\phi} \tag{D-268}$$

where

$$A_{39F} = I_{xs} \dot{\omega}_x + \omega_y \omega_z (I_{zs} - I_{ys}) \tag{D-269}$$

$$A_{40F} = I_{zs} \omega_y \tag{D-270}$$

Y-Component of Moment Equation.

Equation D-258 becomes

$$-L_u F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L} = A_{41F} + A_{42F} \dot{\phi} \tag{D-271}$$

where

$$A_{41F} = I_{ys} \dot{\omega}_y + \omega_x \omega_z (I_{xs} - I_{zs}) \tag{D-272}$$

$$A_{42F} = -I_{zs} \omega_y \tag{D-273}$$

Z-Component of Moment Equation.

For present purposes equation D-259 remains as it is.

Solution of Escape Wheel Pivot Forces. To derive expressions for the escape wheel pivot forces, equations D-260, D-264, D-268, and D-271 must be solved simultaneously. To obtain the same general form as in equation D-67, equations D-260 and D-264 are multiplied by (-1). The resulting form may then use the solution to equation D-67. Note that A_{11} in equation D-67 is now replaced by μ. Then

$$\begin{bmatrix} -1 & \mu & 1 & -\mu \\ -\mu & -1 & \mu & 1 \\ \mu L_u & L_u & \mu L_L & L_L \\ -L_u & \mu L_u & -L_L & \mu L_L \end{bmatrix} \begin{bmatrix} F_{x3u} \\ F_{y3u} \\ F_{x3L} \\ F_{y3L} \end{bmatrix} = \begin{bmatrix} B_{s1f} \\ B_{s2f} \\ B_{s3f} \\ B_{s4f} \end{bmatrix} \qquad \text{(D-274)}$$

where

$$B_{s1f} = -[P_n A_{33F} + F_{23} A_{34F} + A_{35F}] \qquad \text{(D-275)}$$

$$B_{s2f} = -[P_n A_{36F} + F_{23} A_{37F} + A_{38F}] \qquad \text{(D-276)}$$

$$B_{s3f} = A_{39F} + A_{40F}\dot{\phi} \qquad \text{(D-277)}$$

$$B_{s4f} = A_{41F} + A_{42F}\dot{\phi} \qquad \text{(D-278)}$$

Evaluation of the Coefficient Determinant D.

The solution for the coefficient determinant D of equation D-274 is identical to equation D-72. With A_{11} now being equal to μ, the following expression, parallel to equation D-75, is obtained

$$D = \left[(L_u + L_L)(1 + \mu^2) \right]^2 \qquad \text{(D-279)}$$

Evaluation of Pivot Force $\tilde{F}_{x3u}$.

The pivot force F_{x3u} is obtained from

$$F_{x3u} = \frac{D_{F_{x3u}}}{D} \qquad \text{(D-280)}$$

where

$$D_{F_{x3u}} = \begin{vmatrix} B_{s1f} & \mu & 1 & -\mu \\ B_{s2f} & -1 & \mu & 1 \\ B_{s3f} & L_u & \mu L_L & L_L \\ B_{s4f} & \mu L_u & -L_L & \mu L_L \end{vmatrix} \tag{D-281}$$

If μ is substituted for A_{11} in equation D-77, the identical form as above is obtained and the solution of equation D-80 can be adapted

$$D_{F_{x3u}} = \left(1 + \mu^2\right)\left(L_u + L_L\right)\left[-L_L B_{s1f} - \mu L_L B_{s2f} + \mu B_{s3f} - B_{s4f}\right] \tag{D-282}$$

Now equations D-275 and D-278 are substituted into the above expression and the coefficients of similar terms are collected. In order to get conservative pivot and pivot friction forces, the latter terms are made absolute. Finally, the tilded force $\widetilde{F}_{x3u}$ is obtained from the appropriate change of equation D-280

$$\widetilde{F}_{x3u} = \frac{\widetilde{D}_{F_{x3u}}}{D} = \frac{1}{\left(L_u + L_L\right)\left(1 + \mu^2\right)}\left[C_{21F} + C_{22F}P_n + C_{23F}F_{23F} + C_{24F}\dot{\phi}\right] \tag{D-283}$$

where

$$C_{21F} = \left|L_L A_{35F} - A_{41F} + \mu\left(L_L A_{38F} + A_{39F}\right)\right| \tag{D-284}$$

$$C_{22F} = \left|L_L\left(A_{33F} + \mu A_{36F}\right)\right| \tag{D-285}$$

$$C_{23F} = \left|L_L\left(A_{34F} + \mu A_{37F}\right)\right| \tag{D-286}$$

$$C_{24F} = \left|\mu A_{40F} - A_{42F}\right| \tag{D-287}$$

Evaluation of Pivot Force $\tilde{F}_{y3u}$.

The pivot force F_{y3u} is obtained from

$$F_{y3u} = \frac{D_{F_{y3u}}}{D} \qquad \text{(D-288)}$$

where

$$D_{F_{y3u}} = \begin{vmatrix} -1 & B_{s1f} & 1 & -\mu \\ -\mu & B_{s2f} & \mu & 1 \\ \mu L_u & B_{s3f} & \mu L_L & L_L \\ -L_u & B_{s4f} & -L_L & \mu L_L \end{vmatrix} \qquad \text{(D-289)}$$

Since the form of the above is the same as that of the determinant of equation D-88b, equation D-90, which represents the solution of the latter, may be adaptedas follows

$$D_{F_{y3u}} = (L_u + L_L)(1 + \mu^2)[\mu L_L B_{s1f} - L_L B_{s2f} + B_{s3f} + \mu B_{s4f}] \qquad \text{(D-290)}$$

Again, substitue the B_{si} terms of equations D-275 to D-278, collect the coefficients of similar terms, and make the result absolute. The tilded pivot force $\tilde{F}_{y3u}$ then becomes parallel to equation D-201

$$\tilde{F}_{y3u} = \frac{\tilde{D}_{F_{y3u}}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)}\left[C_{25F} + C_{26F}P_n + C_{27F}F_{23F} + C_{28F}\dot{\phi}\right] \qquad \text{(D-291)}$$

where

$$C_{25F} = |L_L A_{38F} + A_{39F} + \mu(A_{41F} - L_L A_{35F})| \qquad \text{(D-292)}$$

$$C_{26F} = |L_L (A_{36F} - \mu A_{33F})| \qquad \text{(D-293)}$$

$$C_{27F} = |L_L (A_{37F} - \mu A_{34F})| \qquad \text{(D-294)}$$

$$C_{28F} = |\mu A_{40F} + \mu A_{42F}| \qquad \text{(D-295)}$$

Evaluation of Pivot Force $\tilde{F}_{x3L}$.

The pivot force F_{x3L} is obtained from

$$F_{x3L} = \frac{D_{F_{x3L}}}{D} \qquad \text{(D-296)}$$

where

$$D_{F_{x3L}} = \begin{vmatrix} -1 & \mu & B_{s1f} & -\mu \\ -\mu & -1 & B_{s2f} & 1 \\ \mu L_u & L_u & B_{s3f} & L_L \\ -L_u & {}^{-}L_u & B_{s4f} & \mu L_L \end{vmatrix} \qquad \text{(D-297)}$$

Since the form of the above is the same as that of equation D-98, equation D-100 may be adapted, i.e.

$$D_{F_{x3L}} = (L_u + L_L)(1 + \mu^2)[L_u B_{s1f} + \mu L_u B_{s2f} + \mu B_{s3f} - B_{s4f}] \qquad \text{(D-298)}$$

Again, the B_{si} terms are substituted according to equations D-275 to D-278 and the requisite work obtains the tilded determinant $\tilde{D}_{F_{x3L}}$. Then

$$\tilde{F}_{x3L} = \frac{\tilde{D}_{F_{x3L}}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)}\left[C_{29F} + C_{30F}P_n + C_{31F}F_{23F} + C_{32F}\dot{\phi}\right] \qquad \text{(D-299)}$$

where

$$C_{29F} = |\mu\,(A_{39F} - L_u A_{38F}) - L_u A_{35F} - A_{41}\;| \qquad \text{(D-300)}$$

$$C_{30F} = |L_u\,(A_{33F} + \mu A_{36F})\,| \qquad \text{(D-301)}$$

$$C_{31F} = |L_u\,(A_{34F} + \mu A_{37F})\,| \qquad \text{(D-302)}$$

$$C_{32F} = |\mu A_{40F} - A_{42F}| \qquad \text{(D-303)}$$

Evaluation of Pivot Force $\tilde{F}_{y3L}$.

The pivot force F_{y3L} is obtained from

$$F_{y3L} = \frac{D_{F_{y3L}}}{D} \tag{D-304}$$

$$D_{F_{y3L}} = \begin{vmatrix} -1 & \mu & 1 & B_{s1f} \\ -\mu & -1 & \mu & B_{s2f} \\ \mu L_u & L_u & \mu L_L & B_{s3f} \\ -L_u & \mu L_u & -L_L & B_{s4f} \end{vmatrix} \tag{D-305}$$

Since the form of the above is the same as that of equation D-108, equation D-110 may be adapted to the present situation, therefore

$$D_{F_{y3L}} = (L_u + L_L)\left(1 + \mu^2\right)\left[-\mu L_u B_{s1f} + L_u B_{s2f} + B_{s3f} + \mu B_{s4f}\right] \tag{D-306}$$

The B_{si} terms are substituted according to equations D-275 to D-278, terms are collected and the tilded pivot force is defined

$$\tilde{F}_{y3L} = \frac{\tilde{D}_{F_{y3L}}}{D} = \frac{1}{(L_u + L_L)\left(1 + \mu^2\right)}\left[C_{33F} + C_{34F}P_n + C_{35F}F_{23F} + C_{36F}\dot{\phi}\right] \tag{D-307}$$

where

$$C_{33F} = \left|\mu\left(A_{41F} + L_u A_{35F}\right) + A_{39F} - L_u A_{38F}\right| \tag{D-308}$$

$$C_{34F} = \left|L_u\left(\mu A_{33F} - A_{36F}\right)\right| \tag{D-309}$$

$$C_{35F} = \left|L_u\left(\mu A_{34F} - \mu A_{37F}\right)\right| \tag{D-310}$$

$$C_{36F} = \left|A_{40F} + \mu A_{42F}\right| \tag{D-311}$$

Determinations of Contact Force P_n in Terms of Escape Wheel Parameters (Round-on-Flat Contact)

Substitution of Conservative (Tilded) Pivot Forces into the z-Component of the Moment Equation. Again, let the sum of the tilded pivot forces be first determined. Subsequently, this expression is subsituted into the moment equation D-259. Then

$$\tilde{F}_{x3u} + \tilde{F}_{y3u} + \tilde{F}_{x3L} + \tilde{F}_{y3L} = A_{43F} + A_{44F}P_n + A_{45F}F_{23F} + A_{46F}\dot{\phi} \qquad \text{(D-312)}$$

where

$$L_T = L_U + L_L \qquad \text{(D-313)}$$

$$A_{43F} = \frac{C_{21F} + C_{25F} + C_{29F} + C_{33F}}{L_T(1 + \mu^2)} \qquad \text{(D-314)}$$

$$A_{44F} = \frac{C_{22F} + C_{26F} + C_{30F} + C_{34F}}{L_T(1 + \mu^2)} \qquad \text{(D-315)}$$

$$A_{45F} = \frac{C_{23F} + C_{27F} + C_{31F} + C_{35F}}{L_T(1 + \mu^2)} \qquad \text{(D-316)}$$

$$A_{46F} = \frac{C_{24F} + C_{28F} + C_{32F} + C_{36F}}{L_T(1 + \mu^2)} \qquad \text{(D-317)}$$

Equation D-312 is now substituted into equation D-259. As earlier, for round-on-round contact the force F_{z3} of equation D-253 is made conservative, i.e.

$$\tilde{F}_{z3} = A_{47} = |N_z m_3| \qquad \text{(D-318)}$$

Equation D-259 then becomes

$$-P_n\left(A_1' - B_1\mu_1 s_4\right) - F_{23F}g_2 - \mu\rho_{f3}A_{47F} - \mu\rho_3\left[A_{43F} + A_{44F}P_n \right.$$

$$\left. + A_{45F}F_{23F} + A_{46F}\dot{\phi}\right] = I_{zs}\dot{\omega}_z + I_{zs}\ddot{\phi} \qquad \text{(D-319)}$$

Similar to what was done in equations D-236 and D-237, and for the same reasons, indicated near these expressions, the friction moment term $-\mu\rho_3 A_{46F}\dot{\phi}$ above is now modified to read

$$-\mu\rho_3 A_{46F}\frac{\dot{\phi}^2}{|\dot{\phi}|} \tag{D-320}$$

Equation D-319 then becomes

$$P_n\left[-A_1' + B_1'\mu_1 s_4 - \mu\rho_3 A_{44F}\right] + F_{23F}g_2 - \mu\rho_3 A_{46F}\frac{\dot{\phi}^2}{|\dot{\phi}|}$$

$$-\mu\left[\rho_{f3}A_{47F} + \rho_3 A_{43F}\right] = I_{zs}\ddot{\phi} + I_{zs}\dot{\omega}_z \tag{D-321}$$

Finally, the above furnishes the contact force P_n

$$P_n = \frac{I_{zs}\ddot{\phi} + A_{48F}\dot{\phi}^2 + F_{23F}A_{49F} + A_{50F}}{A_{51F}} \tag{D-322}$$

where

$$A_{48F} = \frac{\mu\rho_3 A_{46F}}{|\dot{\phi}|} \tag{D-323}$$

$$A_{49F} = -g_2 \tag{D-324}$$

$$A_{50F} = I_{zs}\dot{\omega}_z + \mu\left[\rho_{f3}A_{47F} + \rho_3 A_{43F}\right] \tag{D-325}$$

$$A_{51F} = B_1'\mu_1 s_4 - A_1' - \mu\rho_3 A_{44F} \tag{D-326}$$

Combined Entrance Coupled Motion Differential Equation with Mesh 2 in Round-on-Flat Contact

Equations D-140 and D-322 are now set equal to each other. This furnishes the following combined coupled motion differential equation for the escapement under entrance conditions and with mesh 2 in the round-on-flat phase of contact

$$[A_{51F}I_{PR}U - A_{29}I_{zs}]\ddot{\phi} + \left[A_{51F}\left(A_{32}U^2 + I_{PR}V\right) - A_{29}A_{48F}\right]\dot{\phi}^2$$

$$+ A_{51F}A_{31F}U\dot{\phi} = F_{23F}A_{29}A_{49F} + A_{29}A_{50F} - A_{51F}\left(A_9 + A_{30}\right)$$

$$+ A_{51F}m_p r_{cp}(K_x \sin\beta - K_y \cos\beta) \qquad \text{(D-327)}$$

Pallet and Escape Wheel in Exit Coupled Motion

Pallet Equations

The free body diagram of the pallet for exit coupled motion is given by figures D-7a and D-7b. Now (see refs 1 and 2)

$$\bar{P}_n = -P_n\bar{n}_n \qquad \text{(D-328)}$$

This sign change will be reflected both in the force and in the moment expressions. The following shows the relevant changes in equations D-23 and D-140.

Changes in Force Equations of Pallet

Equation D-24 is modified to accommodate equation D-328. The associated friction forces have their directions determined by the signum functions s_4 and s_5, as before. Therefore, equation D-24 is changed in its first term only

$$-P_n\bar{n}_n + \mu_1 s_4 P_n\bar{n}_t + \ldots\ldots \qquad \text{(D-329)}$$

With the unit vectors of equations D-25 and D-26, the x′-force equation D-27 is modified to

$$P_n\sin(\psi + \alpha) + \mu_1 s_4 P_n\cos(\psi + \alpha) - F_{x'u} - \mu_1 s_5 F_{y'u} + F_{x'L} + \ldots\ldots \qquad \text{(D-330)}$$

The terms in the y′-expression D-28 are changed as follows

$$-P_n\cos(\psi + \alpha) + \mu_1 s_4 P_n\sin(\psi + \alpha) - F_{y'u} - \mu_1 s_5 F_{x'u} + F_{y'L} + \ldots\ldots \qquad \text{(D-331)}$$

The expression for $F_{z'}$ remains as given by equation D-29.

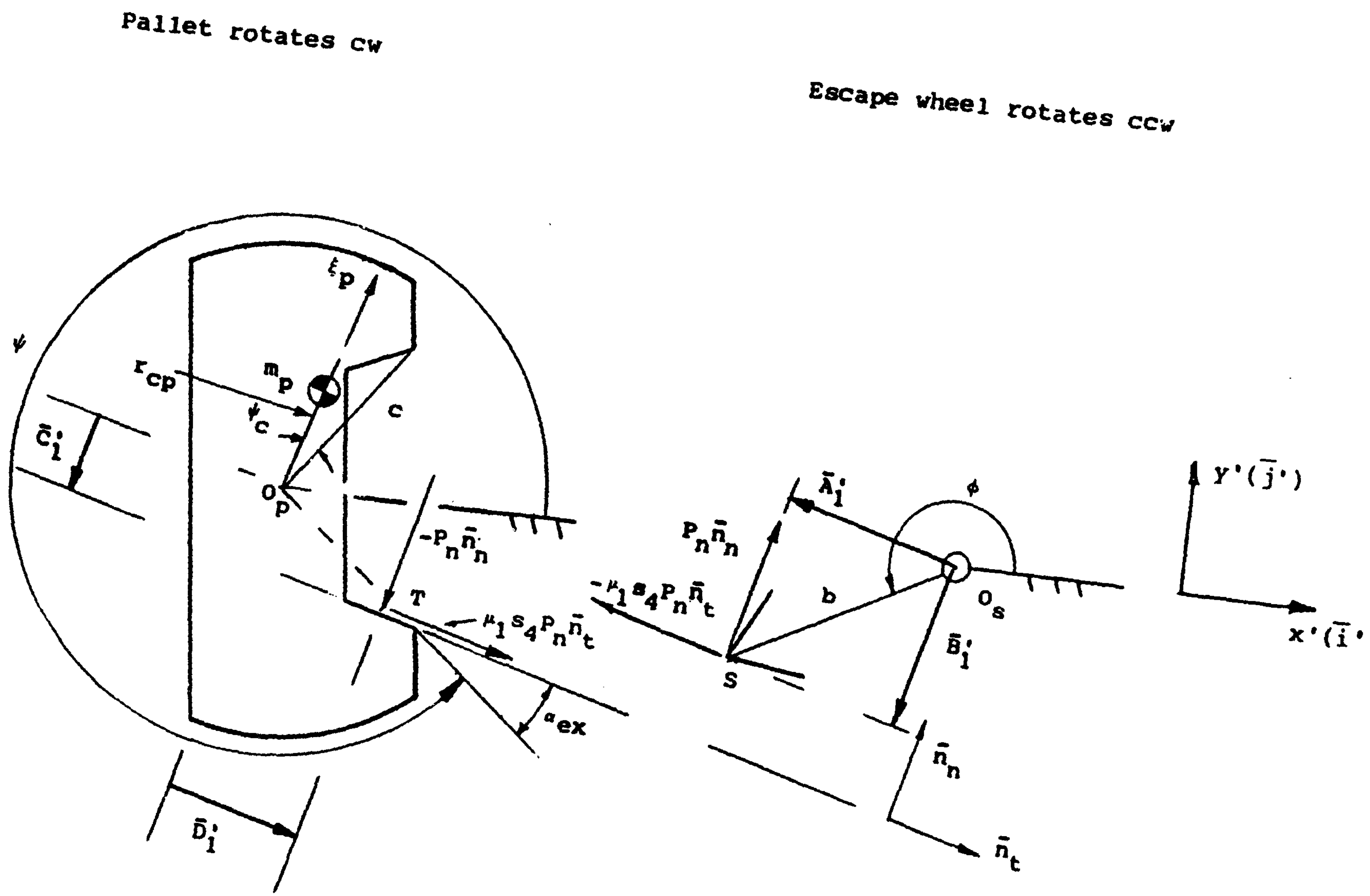


Figure D-7a. Top view free body diagram of pallet in exit coupled motion

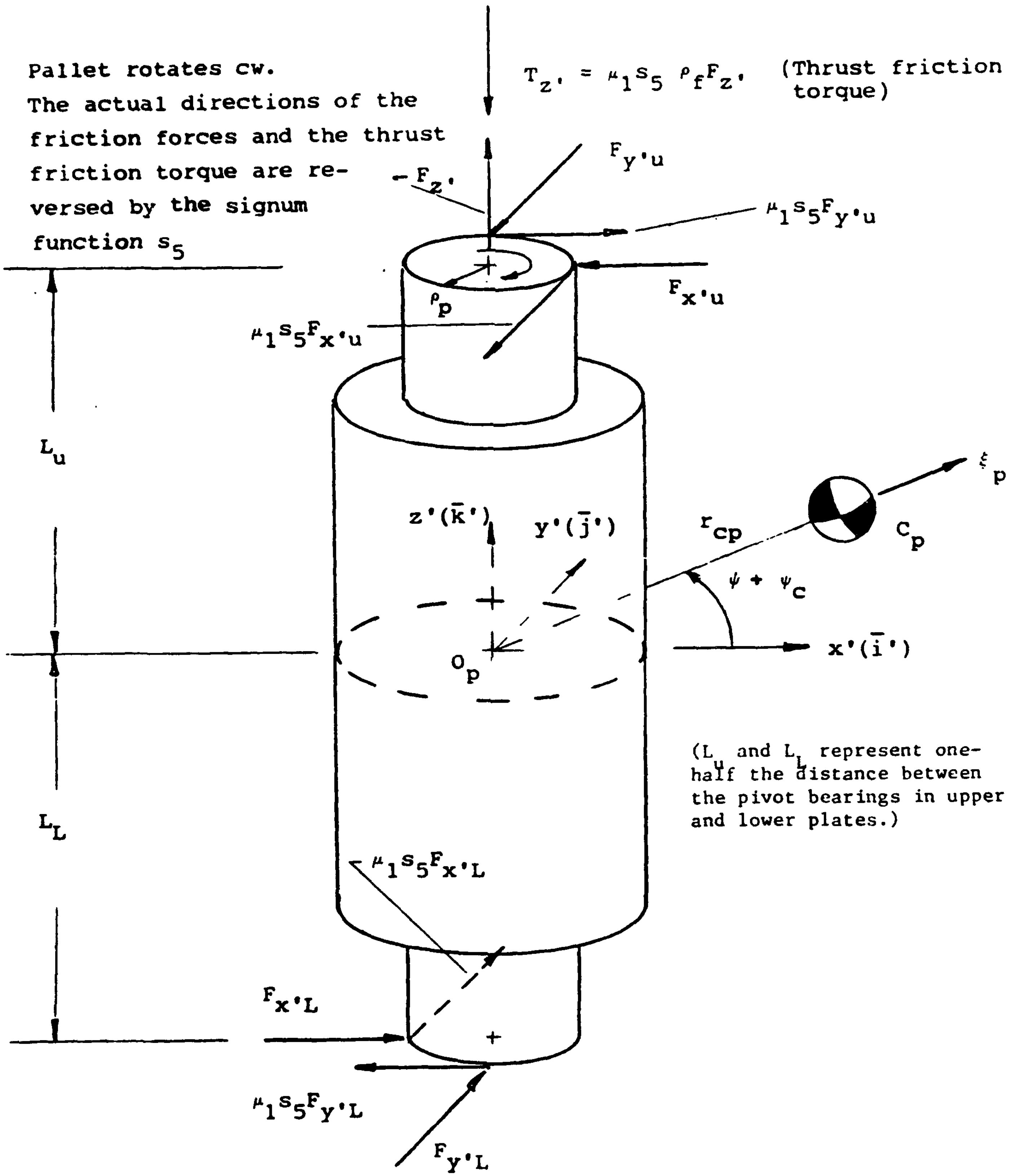


Figure D-7b. Pallet in exit coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots.

Changes in Moment Equations of Pallet

The form of P_n, according to equation D-328, also reflects itself in the expression for $\overline{M}_{OP}$ (eq D-31). Therefore, for the exit case

$$\overline{M}_{OP} = D_1 P_n \overline{k}' - \mu_1 s_4 C_1 P_n \overline{k}' \ldots \quad \text{(D-332)}$$

Simplification of Force and Moment Equations and Determination of Pallet Pivot Forces

x′-Force Component

Due to the change shown in equation D-330, the parameter A_{16} in equation D-48 must be changed to become

$$AA_{16} = -[\mu_1 s_4 \cos(\psi + \alpha) - \sin(\psi + \alpha)] \quad \text{(D-333)}$$

y′-Force Component

Similarly, because of the change in equation D-331, the parameter A_{21} in equation D-55 must be changed to

$$AA_{21} = -[\mu_1 s_4 \sin(\psi + \alpha) - \cos(\psi + \alpha)] \quad \text{(D-334)}$$

z′-Force Component

The z′-force component remains as that given by equation D-61, as stated earlier.

x′- and y′-Moment Component Equations

The x′- and y′-moment component equations remain unchanged from equations D-64 and D-65, respectively, since they do not contain P_n.

z′-Moment Component Equation

Because of the changes shown in equation D-332, the z′-moment component expression D-66 must now be modified to read

$$-P_n\left(D_1' + \mu_1 s_4 C_1'\right) - \rho_f A_{11} F_{z'} - \rho_p A_{11} F_{y'u} - \rho_p A_{11} F_{x'u}$$

$$- \rho_p A_{11} F_{y'L} - \rho_p A_{11} F_{x'L} = -m_p r_{cp}\left(K_x \sin\beta - K_y \cos\beta\right) + A_9 + A_{10}\ddot{\psi} \quad \text{(D-335)}$$

Solution of Pallet Pivot Forces. The solution for the pivot forces $F_{x'u}$, $F_{y'u}$, $F_{x'L}$, and $F_{y'L}$ is identical to that shown for the entrance coupled motion, keeping in mind that now the parameters AA_{16} and AA_{21} are used instead of A_{16} and A_{21}. Equation D-117 must subsequently be changed to

$$\tilde{F}_{x'u} + \tilde{F}_{y'u} + \tilde{F}_{x'L} + \tilde{F}_{y'L} = A_{24} + \dot{\psi}A_{25} + \dot{\psi}^2 A_{26} + \ddot{\psi}A_{27} + P_n AA_{28} \qquad \text{(D-336)}$$

A_{24} and A_{27} remain the same; so does AA_{28} as long as it is realized that it contains AA_{16} and AA_{21} (eq D-122a).

Substitution of Pallet Pivot Forces into z′-Moment Component Equation: Determination of P_n. Because of the changes in equation D-335, and using the same reasoning as employed for equations D-123 to D-128, equation D-129 becomes for exit coupled motion

$$P_n AA_{29} - A_{30} - A_{31}\dot{\psi} - A_{32}\dot{\psi}^2$$

$$= I_{PR}\ddot{\psi} + A_9 - m_p r_{cp}\left(K_x \sin\beta - K_y \cos\beta\right) \qquad \text{(D-337)}$$

where

$$AA_{29} = -\left[D_1' + C_1'\mu_1 s_4 + \rho_p \mu_1 s_5 AA_{28}\right] \qquad \text{(D-338)}$$

Finally, parallel to equation D-137, the contact force P_n becomes

$$P_n = \frac{I_{PR}\ddot{\psi} + A_9 + A_{30} + A_{31}\dot{\psi} + A_{32}\dot{\psi}^2 - m_p r_{cp}\left(K_x \sin\beta - K_y \cos\beta\right)}{AA_{29}} \qquad \text{(D-339)}$$

If this expression is rewritten in terms of the escape wheel variables $\dot{\phi}$ and $\ddot{\phi}$ the following equation which is similar to equation D-140 is obtained

$$P_n = \frac{1}{AA_{29}}\left[I_{PR}U\ddot{\phi} + \left(A_{32}U^2 + I_{PR}V\right)\dot{\phi}^2 + A_{31}U\dot{\phi}\right.$$

$$\left. + A_9 + A_{30} - m_p r_{cp}\left(K_x \sin\beta - K_y \cos\beta\right)\right] \qquad \text{(D-340)}$$

Changes in Force Equations of Escape Wheel and Pinion No. 3 in Exit Coupled Motion with Mesh No. 2 in Round-on-Round Contact

The free body diagram of the escape wheel and pinion no. 3 in exit coupled motion, with mesh no. 2 in round-on-round contact is shown in figures D-8a and D-8b. When compared to figure D-5a, the contact force $\overline{P}_n$ and its associated friction force are now different, i.e., they account for exit coupled motion.

Equation D-165 must be modified to read

$$P_n\overline{n}_n - \mu_1 s_4 P_n \overline{n}_t + F_{23}\overline{n}_{\lambda 2} + \mu s_{2R} F_{23}\overline{n}_{N\lambda 2} + \dots \tag{D-341}$$

With the unit vectors of equations D-143 and D-144, the X-force component equation (changed from D-166) becomes

$$P_n \sin(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \cos(\psi + \alpha + \beta_3) + F_{23}\cos\lambda_2$$

$$- \mu s_{2R} F_{23} \sin\lambda_2 - F_{x3u} + \mu F_{y3u} + F_{x3L} - \mu F_{y3L} = N_x m_3 \tag{D-342}$$

The Y-force component is changed from equation D-167 to read

$$-P_n \cos(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \sin(\psi + \alpha + \beta_3) + F_{23}\sin\lambda_2$$

$$+ \mu s_{2R} F_{23} \cos\lambda_2 - F_{y3u} - \mu F_{x3u} + F_{y3L} + \mu F_{x3L} = N_y m_3 \tag{D-343}$$

The Z-force component remains as in equations D-168, i.e.,

$$F_{z3} = N_3 m_3 \tag{D-344}$$

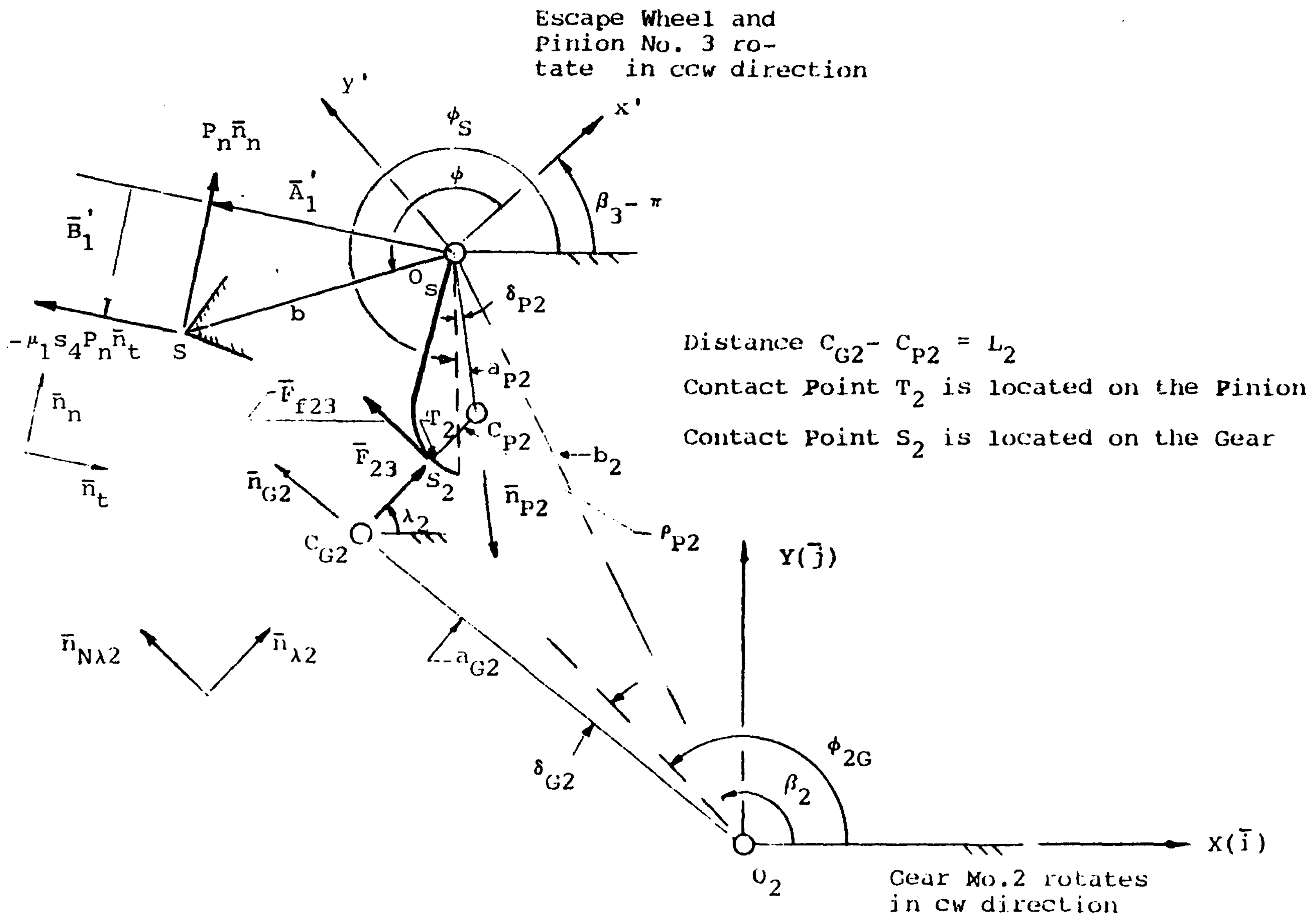


Figure D-8a. Top view of escape wheel and pinion no. 3 in exit coupled motion. Round-on-round contact of mesh no. 2

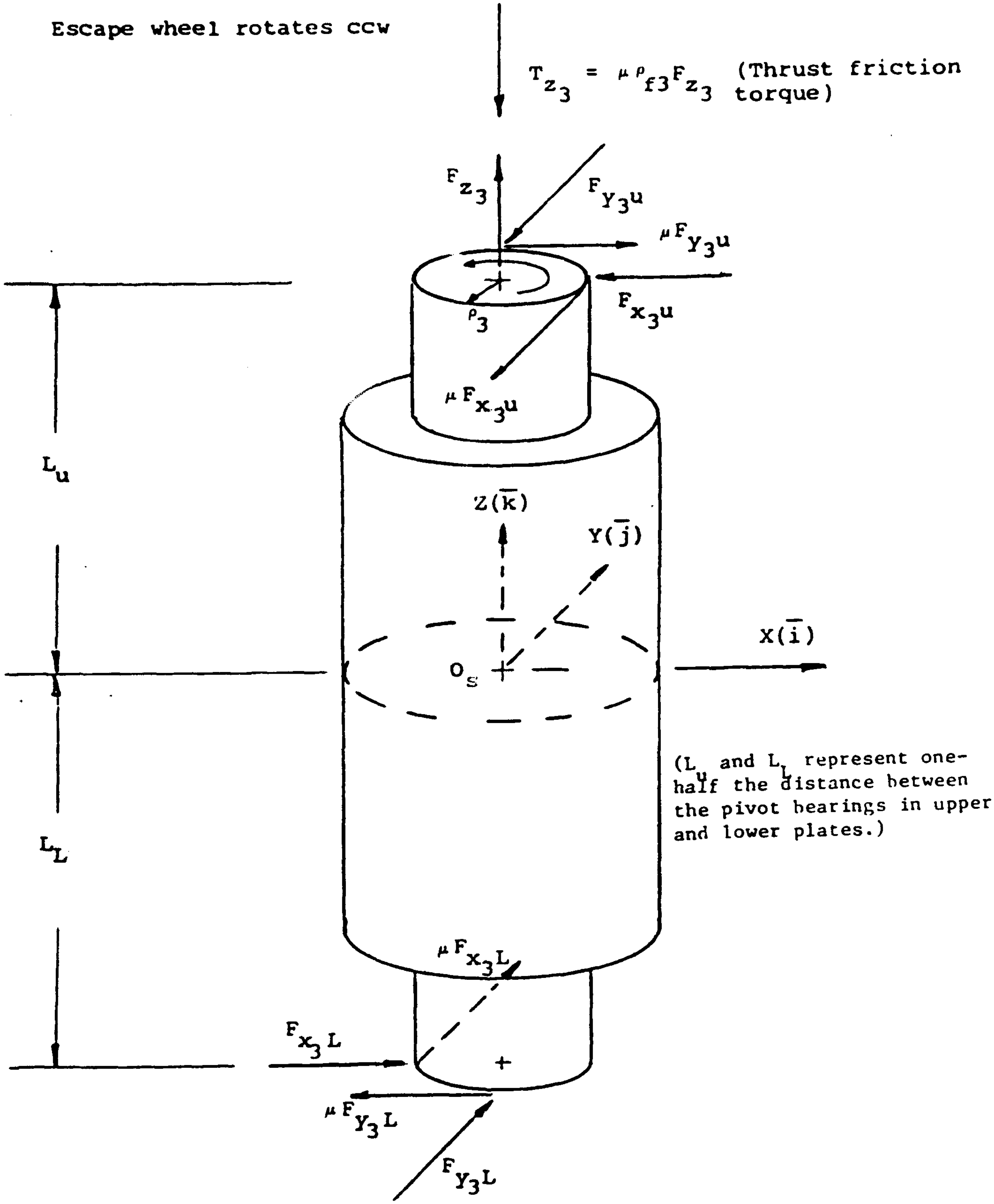


Figure D-8b. Escape wheel and pinion no. 3 in exit coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots. (Not influenced by type of mesh contact.)

Changes in Moment Equations of Escape Wheel and Pinion No. 3 in Exit Coupled Motion with Mesh No. 2 in Round-on-Round Contact

Changes in Moment Equations of Escape Wheel. The moment equation D-169 for the escape wheel and pinion no. 3 must also reflect the change in P_n. The lefthand side of the above expression, as given by equation D-170 must be modified, because now the cross product

$$A_1\bar{n}_t x P_n \bar{n}_n = P_n A_1' \bar{k} \qquad \text{(D-346)}$$

This results in the following change to equation D-170

$$P_n\left(A_1' + B_1'\mu_1 s_4\right)\bar{k} - \mu\rho_{t3}F_{z3}\bar{k} + \ldots\ldots \qquad \text{(D-346)}$$

The righthand side of equation D-167 remains unchanged. The resulting X and Y moment component expressions, i.e., equations D-173 and D-174, respectively, are not influenced by the above change. The Z-moment component expression D-175 must now read

$$P_n\left(A_1' + B_1'\mu_1 s_4\right) + a_{P2}F_{23}\left(\sin\left(\lambda_2 - \phi_s - \delta_{p2}\right)\right.$$
$$\left. + \mu s_{2R}\cos\left(\lambda_2 - \phi_s - \delta_{p2}\right)\right) - \ldots\ldots \qquad \text{(D-347)}$$

Simplification of Force and Moment Equations and Determination of Escape Wheel Pivot Forces

X-Force Component

Due to the change in equation D-342 the parameter A_{33R} in equation D-176 must be changed to

$$AA_{33R} = \mu_1 s_4 \cos(\psi + \alpha + \beta_3) + \sin(\psi + \alpha + \beta_3) \qquad \text{(D-348)}$$

Y-Force Component

Similarly, because of the change in equation D-343 the parameter A_{36R} in equation D-189 now becomes

$$AA_{36R} = \mu_1 s_4 \sin(\psi + \alpha + \beta_3) - \cos(\psi + \alpha + \beta_3) \tag{D-349}$$

Z-Force Component

The Z-force component remains presently as given by equation D-344.

As stated earlier, the X- and Y-components of the moment expressions for the escape wheel need not be changed. They are used in their final form as given by equations D-184 and D-187, respectively. Therefore, the X-component of the moment equations is given by

$$\mu L_u F_{x3u} + L_u F_{y3u} + \mu L_L F_{x3L} + L_L F_{y3L} = A_{39R} + A_{40R}\dot{\phi} \tag{D-350}$$

The Y-component of the moment equation is

$$-L_u F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L} = A_{41R} + A_{42R}\dot{\phi} \tag{D-351}$$

Solution of Escape Wheel Pivot Forces for Exit Coupled Motion. Since only the parameters AA_{33R} and A_{36R} differ in the set simultaneous equations D-176, D-181, D-350, and D-351 from those used in the solution for the pivot forces in entrance coupled motion, the latter is adapted to the present situation. Then, according to equation D-199

$$\tilde{F}_{x3u} = \frac{1}{(L_u + L_L)(1 + \mu^2)}\left[C_{21R} + CC_{22R}P_n + C_{23R}F_{23} + C_{24R}\dot{\phi}\right] \tag{D-352}$$

where, now

$$CC_{22R} = |L_L(AA_{33R} + \mu AA_{36R})| \tag{D-353}$$

and, as before

$$C_{21R} = |L_L A_{35R} - A_{41R} + \mu(L_L A_{38R} + A_{39R})|$$

$$C_{23R} = |L_L(A_{34R} + \mu A_{37R})|$$

$$C_{24R} = |\mu A_{40R} - A_{42R}|$$

According to equation D-207

$$\widetilde{F}_{y3u} = \frac{1}{(L_u + L_L)(1 + \mu^2)}\left[C_{25R} + C_{26R}P_n + C_{27R}F_{23} + C_{28R}\dot{\phi}\right] \qquad \text{(D-354)}$$

where now

$$CC_{26R} = |L_L(AA_{36R} - \mu AA_{33R})| \qquad \text{(D-355)}$$

and, as before

$$C_{25R} = |L_L A_{38R} + A_{39R} + \mu(A_{41R} - L_L A_{35R})|$$

$$C_{27R} = |L_L(A_{37R} - \mu A_{34R})|$$

$$C_{28R} = |A_{40R} + \mu A_{42R}|$$

According to equation D-215

$$\widetilde{F}_{x3L} = \frac{1}{(L_u + L_L)(1 + \mu^2)}\left[C_{29R} + CC_{30R}P_n + C_{31R}F_{23} + C_{32R}\dot{\phi}\right] \qquad \text{(D-356)}$$

where, now

$$CC_{30R} = |L_u(AA_{33R} + \mu AA_{36R})| \qquad \text{(D-357)}$$

and, as before

$$C_{29R} = \left| \mu \left(A_{39R} - L_u A_{38R}\right) - L_u A_{35R} - A_{41R} \right|$$

$$C_{31R} = \left| L_u \left(A_{34R} + \mu A_{37R}\right) \right|$$

$$C_{32R} = \left| \mu A_{40R} - A_{42R} \right|$$

According to equation D-223

$$\tilde{F}_{y3L} = \frac{1}{\left(L_u + L_l\right)\left(1 + \mu^2\right)} \left[C_{33R} + CC_{34R} P_n + C_{35R} F_{23} + C_{36R} \dot{\phi} \right] \qquad \text{(D-358)}$$

where now

$$CC_{34R} = \left| L_u \left(\mu AA_{33R} - AA_{36R}\right) \right| \qquad \text{(D-359)}$$

and, as before

$$C_{33R} = \left| \mu \left(A_{41R} + L_u A_{35R}\right) + A_{39R} - L_u A_{38R} \right|$$

$$C_{35R} = \left| L_u \left(A_{34R} - A_{37R}\right) \right|$$

$$C_{36R} = \left| A_{40R} + \mu A_{42R} \right|$$

Determination of Contact Force P_n in Terms of Escape Wheel Parameters (Exit Coupled Motion and Mesh 2 in Round-on-Round Contact)

Subsitution of Conservative (Tilded) Pivot Forces into Z-Moment Expression. The sum of the tilded pivot forces is identical in form to equation D-228. Therefore with equations D-352, D-354, D-356, and D-358, the following is obtained

$$\tilde{F}_{x3u} + \tilde{F}_{y3u} + \tilde{F}_{x3L} + \tilde{F}_{y3L} = A_{43R} + AA_{44R}P_n + A_{45R}F_{23} + A_{46R}\dot{\phi} \qquad \text{(D-360)}$$

where now

$$AA_{44R} = \frac{CC_{22R} + CC_{26R} + CC_{30R} + CC_{34R}}{L_T\,(1 + \mu^2)} \qquad \text{(D-361)}$$

and, as before

$$A_{43R} = \frac{C_{21R} + C_{25R} + C_{29R} + C_{33R}}{L_T\,(1 + \mu^2)}$$

$$A_{45R} = \frac{C_{23R} + C_{27R} + C_{31R} + C_{35R}}{L_T\,(1 + \mu^2)}$$

$$A_{46R} = \frac{C_{24R} + C_{28R} + C_{32R} + C_{36R}}{L_T\,(1 + \mu^2)}$$

Substitution of equations D-234 (for D-344) and D-360 into equation D-347 furnishes the complete Z-component of the escape wheel moment expression for exit coupled motion with mesh 2 in round-on-round contact

$$P_n\left(A_1' + B_1'\mu_1 s_4\right) + a_{P2}F_{23}\left(\sin\left(\lambda_2 - \phi_s - \delta_{P2}\right) + \mu s_{2R}\cos\left(\lambda_2 - \phi_2 - \delta_{P2}\right)\right)$$

$$- \mu s_{2R}\rho_{P2}F_{23} - \mu\rho_{f3}A_{47} - \mu\rho_3\left[A_{43R} + AA_{44R}P_n + A_{45R}F_{23} + A_{46R}\dot{\phi}\right]$$

$$= I_{ZS}\dot{\omega}_Z + I_{ZS}\ddot{\phi} \qquad \text{(D-362)}$$

Using the same reasoning as given in connection with equations D-236 and D-237, equation D-362 is now solved for P_n. Therefore

$$P_n\left[A_1' + B_1'\mu_1 s_4 - \mu\rho_3 AA_{44R}\right] + F_{23}\left[\alpha_{P2}\left(\sin\left(\lambda_2 - \phi_s - \delta_{P2}\right)\right.\right.$$

$$\left.\left. + \mu s_{2R}\cos\left(\lambda_2 - \phi_s - \delta_{P2}\right)\right) - \mu s_{2R}\rho_{P2} - \mu\rho_3 A_{45R}\right] - \mu\rho_3 A_{46R}\frac{\dot{\phi}^2}{|\dot{\phi}|}$$

$$- \mu\left[\rho_{f3}A_{47} + \rho_3 A_{43R}\right] = I_{zs}\ddot{\phi} + I_{zs}\dot{\omega}_z \tag{D-363}$$

and, similar to equation D-239

$$P_n = \frac{I_{zs}\ddot{\phi} + A_{48R}\dot{\phi}^2 + F_{23}A_{49R} + A_{50R}}{AA_{51R}} \tag{D-364}$$

where now

$$AA_{51R} = A_1' + B_1'\mu_1 s_4 - \mu\rho_3 AA_{44R} \tag{D-365}$$

while as before

$$A_{48R} = \frac{\mu\rho_3 A_{46R}}{|\dot{\phi}|}$$

$$A_{49R} = \mu\left(s_{2R}\rho_{P2} + \rho_3 A_{45R}\right) - a_{P2}\left(\sin\left(\lambda_2 - \phi_s - \delta_{P2}\right) + \mu s_{2R}\cos\left(\lambda_2 - \phi_s - \delta_{P2}\right)\right)$$

$$A_{50R} = I_{zs}\dot{\omega}_z + \mu\left[\rho_{f3}A_{47} + \rho_3 A_{43R}\right]$$

Combined Exit Coupled Motion Differential Equation with Mesh 2 in Round-on-Round Contact

Equations D-339 and D-364 are now set equal to each oher in order to obtain the combined coupled motion differential equation of the escapement under exit conditions and with mesh 2 in round-on-round contact.sh 2 in round-on-round contact.

$$\left[AA_{51R}I_{PR}U - AA_{29}I_{zs}\right]\ddot{\phi} + \left[AA_{51R}\left(A_{32}U^2 + I_{PR}V\right) - AA_{29}A_{48R}\right]\dot{\phi}^2$$

$$+ AA_{51R}A_{31}U\dot{\phi} = F_{23}AA_{29}A_{49R} + AA_{29}A_{50R} - AA_{51R}\left(A_9 + A_{30}\right)$$

$$+ AA_{51R}m_p r_{cp}\left(K_x \sin\beta - K_y \cos\beta\right) \qquad \text{(D-366)}$$

The above expression has the same form as equation D-244, and the difference between the entrance and exit coupled motion depends on the value of the signum function s_7 which is introduced in the next section.

Common Differential Equation and Common Expressions for Entrance and Exit Coupled Motion of Escapement with Mesh No. 2 in Round-on-Round Contact

It is possible to obtain common expressions for both combined entrance and exit coupled motion differential equations with mesh no. 2 in round-on-round contact. (eqs D-244 and D-366).

The AA_{iR}'s and CC_{iR}'s of the exit coupled motion differ only in certain signs from the $A_{iR's}$ and C_{iR}'s, of identical subscript i, associated with entrance coupled motion. This is due only to the differences in escapement geometry.

Common expressions for the above parameters result from the introduction of the signum function s_7, where

s_7 = positive for entrance coupled motion

s_7 = negative for exit coupled motion

With the above, equations D-54 and D-333 are satisified, if

$$A_{16} = AA_{16} = -[\mu_1 s_4 \cos(\psi + \alpha) - s_7 \sin(\psi + \alpha)] \qquad \text{(D-367)}$$

Equations D-60 and D-334 are satisfied, if

$$A_{21} = AA_{21} = -[s_7 \cos(\psi + \alpha) + \mu_1 s_4 \sin(\psi + \alpha)] \qquad \text{(D-368)}$$

Equations D-130 and D-338 are satisfied, if

$$A_{29} = AA_{29} = s_7D_1' - C_1'\mu_1s_4 - \rho_P\mu_1s_5A_{28} \qquad \text{(D-369)}$$

A_{28} appears first in equation D-112a and AA_{28} in equation D-336. Both are functions of A_{16} and A_{21} by way of the appropriate C_i's. (The CC_i's are not specifically given in conjunction with eq D-336.)

Equations D-177 and D-348 are satisfied, if

$$A_{33} = A_{33R} = AA_{33R} = \mu_1s_4\cos(\psi + \alpha + \beta_3) - s_7\sin(\psi + \alpha + \beta_3) \qquad \text{(D-370)}$$

Equations D-181 and D-349 are satisfied, if

$$A_{36} = A_{36R} = AA_{36R} = \mu_1s_4\sin(\psi + \alpha + \beta_3) + s_7\cos(\psi + \alpha + \beta_3) \qquad \text{(D-371a)}$$

In addition, equations D-243 and D-365 are satisfied, if

$$A_{51} = A_{51R} = AA_{51R} = B_1'\mu_1s_4 - s_7A_1' - \mu\rho_3A_{44} \qquad \text{(D-371b)}$$

In the above, $A_{44} = A_{44R} = AA_{44R}$

A_{44R} appears first in equation D-231 and is a function of A_{33R} and A_{36R} by way of the appropriate CC_{iR}'s.

AA_{44R} appears first in equation D-361 and is a function of AA_{33R} and AA_{36R} by way of the appropriate CC_{iR}'s.

As a consequence, it is also to be noted that

$$\left.\begin{aligned} C_{22R} &= CC_{22R} \\ C_{26R} &= CC_{26R} \\ C_{30R} &= CC_{30R} \\ C_{34R} &= CC_{34R} \end{aligned}\right\} \qquad \text{(D-371c)}$$

(eqs D-231 and D-361).

Finally, the combined coupled motion differential equation of the escapement with mesh no. 2 in round-on-round contact becomes, regardless of exit or entrance motion, with equations D-244 and D-366:

$$[A_{51} I_{PR} U - A_{29} I_{zs}]\ddot{\phi} + [A_{51}(A_{32}U^2 + I_{PR}V) - A_{29}A_{48}]\dot{\phi}^2 + A_{51}A_{31}U\dot{\phi}$$

$$= F_{23}A_{29}A_{49R} + A_{29}A_{50} - A_{51}(A_9 + A_{30}) + A_{51}m_p r_{cp}(K_x \sin\beta - K_y \cos\beta) \qquad \text{(D-372)}$$

It will be shown later that the common parameters A_{16}, A_{21}, A_{28}, A_{29}, A_{33}, A_{36}, A_{44}, and A_{51} may also be used when mesh no. 2 is in round-on flat contact. (See work preceding equation D-403.) Further, note that letter subscripts have now been dropped from A_{48} and A_{50}, since these parameters depend on mass or friction only.

Changes in Force Equations of Escape Wheel and Pinion No. 3 in Exit Coupled Motion with Mesh No. 2 in Round-on-Flat Contact

The free body diagram of the escape wheel and the pinion no. 3 in exit coupled motion, with mesh 2 in round-on-flat contact, is shown in figures D-9a and D-9b. Again the contact force P_n and its associated friction force conform to exit coupled motion conditions. The forces F_{23F} and its associated friction force on the flat of the pinion are identical to those shown earlier in figure D-6a. Equation D-249, the force equation for entrance coupled motion with mesh no. 2 in round-on-flat contact, must now be modified to

$$P_n\bar{n}_n - \mu_1 s_4 P_n \bar{n}_t + F_{23F}\bar{n}_{NF2} + \mu s_{2F}\bar{n}_{F2} + F_{z3}\bar{k} - \ldots \qquad \text{(D-373)}$$

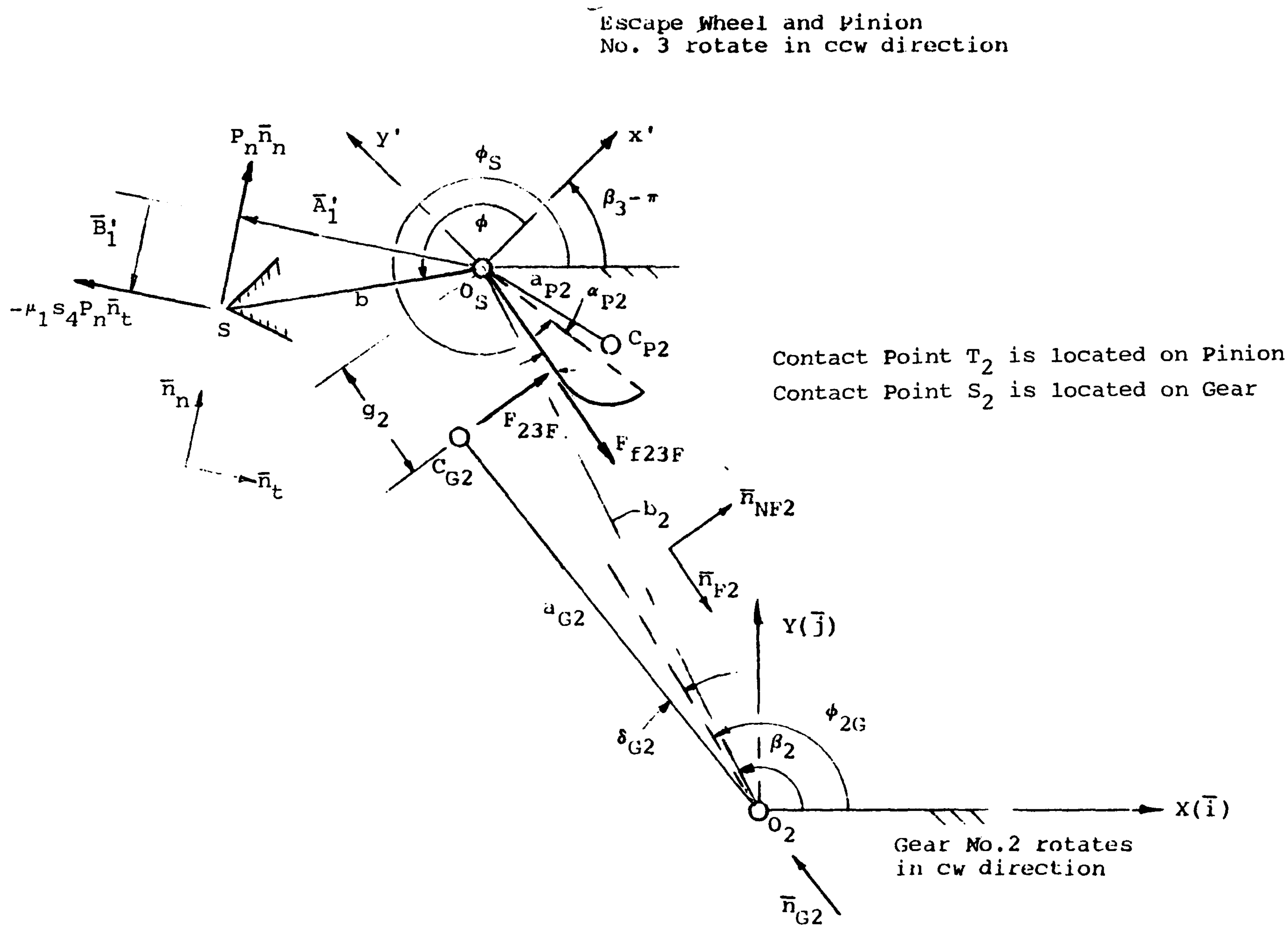


Figure D-9a. Top view of escape wheel and pinion no. 3 in exit coupled motion. Round-on-flat contact of mesh no. 2

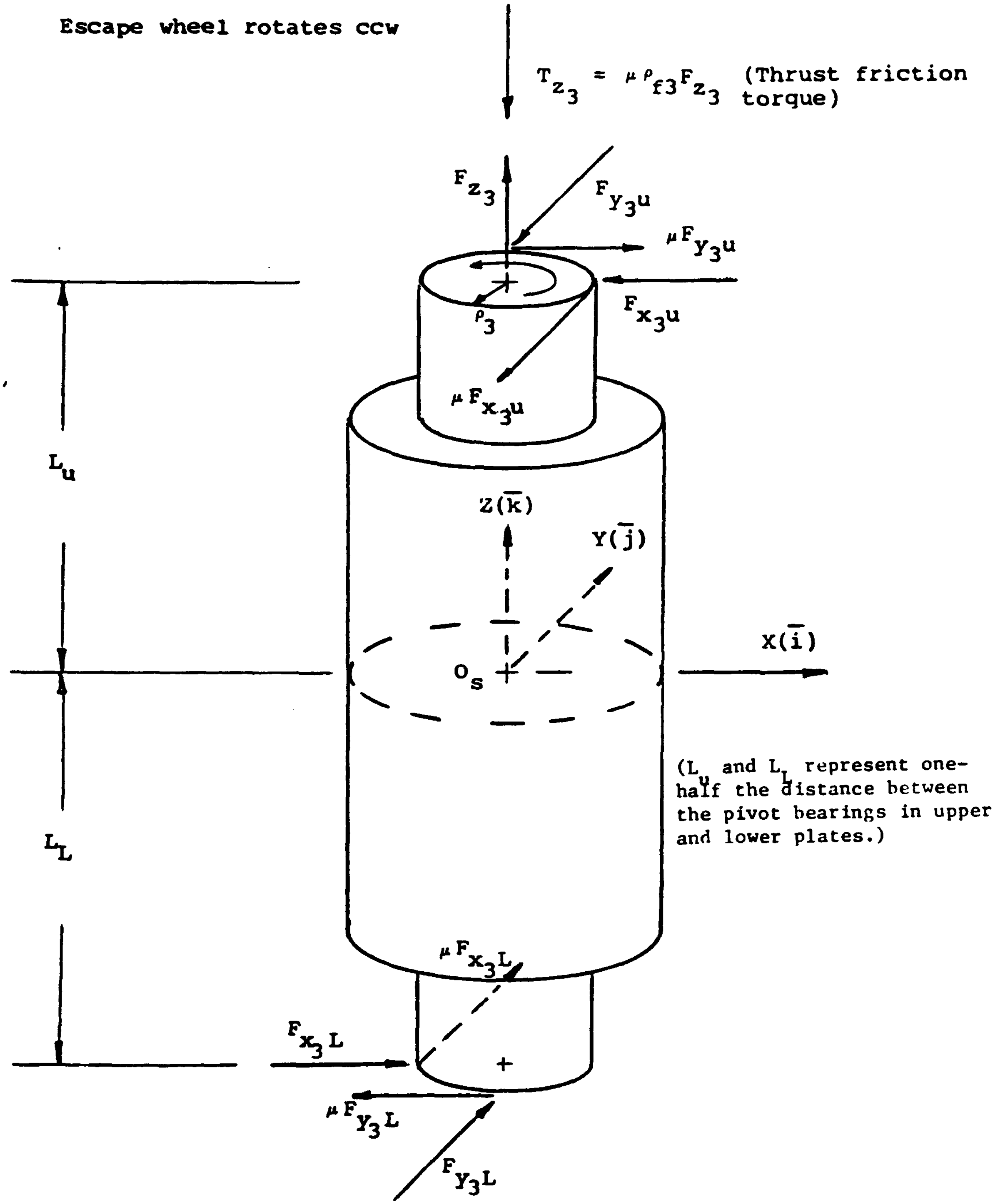


Figure D-9b. Escape wheel and pinion no. 3 in exit coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots. (Same as figure D-8b. Not influenced by type of mesh contact.)

Substitution of the appropriate unit vector, according to equation D-143, D-144, D-245, and D-247, furnishes the following force component equations

X-force component (changed from equation D-251)

$$P_n \sin(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \cos(\psi + \alpha + \beta_3) - F_{23F} \sin(\phi_s - \alpha_{P2})$$

$$+ \mu s_{2F} F_{23F} \cos(\phi_s - \alpha_{P2}) - F_{x3u} + \mu F_{y3u} + F_{x3L} - \mu F_{y3L} = N_x m_3 \qquad \text{(D-374)}$$

The Y-force component is changed from equation D-252 to read

$$- P_n \cos(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \sin(\psi + \alpha + \beta_3) + F_{23F} \cos(\phi_s - \alpha_{P2})$$

$$+ \mu s_{2F} F_{23F} \sin(\phi_s - \alpha_{P2}) - F_{y3u} - \mu F_{x3u} + F_{y3L} + \mu F_{x3L} = N_y m_3 \qquad \text{(D-375)}$$

The Z-force component remains as in equation D-253, i.e.,

$$F_{23} = N_z m_3 \qquad \text{(D-376)}$$

Changes in Moment Equations of Escape Wheel and Pinion No. 2 in Exit Coupled Motion with Mesh No. 2 in Round-on-Flat Contact

As for round-on-round contact, the moment contribution of the escapement forces leads to the following change of equation D-254. (See also equation D-346)

$$P_n (A'_1 + B'_1 \mu_1 s_4)\bar{k} - \mu \rho_{F3} F_{z3} \bar{k} + \dots \qquad \text{(D-377)}$$

The resulting X and Y moment component expressions, i.e., equations D-257 and D-258, respectively, are not influenced by the above change. The Z-component expression D-259 must now be modified to read

$$P_n(A'_1 + B'_1 \mu_1 s_4) + F_{23F} g_2 - \mu \rho_{f3} F_{z3} - \dots \qquad \text{(D-378)}$$

Simplification of Force and Moment Equations and Determination of Escape Wheel Pivot Forces

X-Force Component

Due to the change in equation D-374, the parameter A_{33F} in equation D-261 must be changed to

$$AA_{33F} = \mu_1 s_4 \cos(\psi + \alpha + \beta_3) + \sin(\psi + \alpha + \beta_3) \quad \text{(D-379)}$$

Y-Force Component

Similarly, bec of the change in equation D-375, the parameter A_{36F} in equation D-265 now becon.

$$AA_{36F} = \mu_1 s_4 \sin(\psi + \alpha + \beta_3) - \cos(\psi + \alpha + \beta_3) \quad \text{(D-380)}$$

Z-Force Component

The Z-force component remains presently as given by equation D-376.

As stated earlier, the X- and Y-components of the moment expressions for the escape wheel need not be changed. They are used in their final form as given by equations D-268 and D-271, respectively. Therefore, the X-component of the moment equation is given by

$$\mu L_u F_{x3u} + L_u F_{y3u} + \mu L_L F_{x3L} + L_L F_{y3L} = A_{39F} + A_{40F}\dot{\phi} \quad \text{(D-381)}$$

The Y-component of the moment equation is

$$-L_u F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L} = A_{41F} + A_{42F}\dot{\phi} \quad \text{(D-382)}$$

The Z-component of the moment equation remains in the form of equation D-378.

Solution of Escape Wheel Pivot Forces for Exit Coupled Motion. Since only the parameters AA_{33F} and AA_{36F} differ in the set of simultaneous equations D-374, D-375, D-381, and D-382 from those used in the solution for the pivot forces in entrance coupled motion, the latter is adapted to the present situation. Then, according to equation D-283

$$\tilde{F}_{x3u} = \frac{1}{(L_u + L_L)(1 + \mu^2)}\left[C_{21F} + CC_{22F}P_n + C_{23F}F_{23F} + C_{24F}\dot{\phi}\right] \quad \text{(D-383)}$$

where, now

$$CC_{22F} = |L_L\,(AA_{33F} + \mu AA_{36F})| \tag{D-384}$$

and, as before

$$C_{21F} = |L_L A_{35F} - A_{41F} + \mu(L_L A_{38F} + A_{39F})|$$

$$C_{23F} = |L_L(A_{34F} + \mu A_{37F})|$$

$$C_{24F} = |\mu A_{40F} - A_{42F}|$$

According to equation D-290

$$\tilde{F}_{y3u} = \frac{1}{(L_u + L_L)(1 + \mu^2)}\left[C_{25F} + CC_{26F}P_n + C_{27F}F_{23F} + C_{28F}\dot{\phi}\right] \tag{D-385}$$

where, now

$$CC_{26F} = |L_L\,(AA_{36F} - \mu AA_{33F})| \tag{D-386}$$

and, as before

$$C_{25F} = |L_L A_{38F} + A_{39F} + \mu(A_{41F} - L_L A_{35F})|$$

$$C_{27F} = |L_L(A_{37F} - \mu A_{34F})|$$

$$C_{28F} = |A_{40F} + \mu A_{42F}|$$

According to equation D-299

$$\tilde{F}_{x3L} = \frac{1}{(L_u + L_L)(1 + \mu^2)}\left[C_{29F} + CC_{30F}P_n + C_{31F}F_{23F} + C_{32F}\dot{\phi}\right] \tag{D-387}$$

where, now

$$CC_{30F} = \left|L_u\left(AA_{33F} + \mu AA_{36F}\right)\right| \tag{D-388}$$

and, as before

$$C_{29F} = \left|\mu\left(A_{39F} - L_u A_{38F}\right) - L_u A_{35F} - A_{41F}\right|$$

$$C_{31F} = \left|L_u\left(A_{34F} + \mu A_{37F}\right)\right|$$

$$C_{32F} = \left|\mu A_{40F} - A_{42F}\right|$$

According to equation D-307

$$\tilde{F}_{y3L} = \frac{1}{\left(L_u + L_L\right)\left(1 + \mu^2\right)}\left[C_{33F} + CC_{34F}P_n + C_{35F}F_{23F} + C_{36F}\dot{\phi}\right] \tag{D-389}$$

where, now

$$CC_{34F} = \left|L_u\left(\mu AA_{33F} + AA_{36F}\right)\right| \tag{D-390}$$

and, as before

$$C_{33F} = \left|\mu\left(A_{41F} + L_u A_{35F}\right) + A_{39F} - L_u A_{38F}\right|$$

$$C_{35F} = \left|L_u\left(\mu A_{34F} - A_{37F}\right)\right|$$

$$C_{36F} = \left|A_{40F} + \mu A_{42F}\right|$$

Determination of Contact Force P_n in Terms of Escape Wheel Parameters. (Exit Coupled Motion and Mesh No. 2 in Round-on-Flat Contact)

Substitution of Conservative (Tilded) Pivot Forces into Z-Moment Expressions. The sum of the tilded pivot forces is identical in form to equation D-312. Therefore, with equations D-383, D-385, D-387, and D-389, the following is obtained

$$\tilde{F}_{x3u} + \tilde{F}_{y3u} + \tilde{F}_{x3L} + \tilde{F}_{y3L} = A_{43F} + AA_{44F}P_n + A_{45F}F_{23F} + A_{46F}\dot{\phi} \qquad \text{(D-391)}$$

where now,

$$AA_{44F} = \frac{CC_{22F} + CC_{26F} + CC_{30F} + CC_{34F}}{L_T\left(1 + \mu^2\right)} \qquad \text{(D-392)}$$

and, as before

$$AA_{43F} = \frac{CC_{21F} + CC_{25F} + CC_{29F} + CC_{33F}}{L_T\left(1 + \mu^2\right)}$$

$$AA_{45F} = \frac{CC_{23F} + CC_{27F} + CC_{31F} + CC_{35F}}{L_T\left(1 + \mu^2\right)}$$

$$AA_{46F} = \frac{CC_{24F} + CC_{28F} + CC_{32F} + CC_{36F}}{L_T\left(1 + \mu^2\right)}$$

Substitution of equations D-318 and D-391 into equation D-378 furnishes the complete Z-component of the escape wheel moment expression for exit coupled motion.

$$P_n\left(A_1' + B_1'\mu_1 s_4\right) + F_{23F}g_2 - \mu\rho_{13}A_{47} - \mu\rho_3\left[A_{43F} + AA_{44F}P_n\right.$$

$$\left. + A_{45F}F_{23F} + A_{46F}\dot{\phi}\right] = I_{zs}\dot{\omega}_z + I_{zs}\ddot{\phi} \qquad \text{(D-393)}$$

Using the same reasoning as given in connection with equations D-236 and D-237, equation D-393 is now solved for P_n. Therefore

$$P_n\left[A_1' + B_1'\mu_1 s_4 - \mu\rho_3 AA_{44F}\right] + F_{23F}g_2 - \mu\rho_3 A_{46}\frac{\dot{\phi}^2}{|\dot{\phi}|}$$

$$- \mu\left[\rho_{f3}A_{47} + \rho_3 A_{43}\right] = I_{zs}\ddot{\phi} + I_{zs}\dot{\omega}_z$$

and, similar to equation D-322

$$P_n = \frac{I_{zs}\ddot{\phi} + A_{48F}\dot{\phi}^2 + F_{23F}A_{49F} + A_{50F}}{AA_{51F}} \qquad \text{(D-395)}$$

where now

$$AA_{51F} = A'_1 + B'_1\mu_1 s_4 - \mu\rho_3 AA_{44F} \qquad \text{(D-396)}$$

while as before

$$A_{48F} = \frac{\mu\rho_3 A_{46F}}{|\dot{\phi}|}$$

$$A_{49F} = g_2$$

$$A_{50F} = I_{zs}\dot{\omega}_z + \mu[\rho_{f3}A_{47} + \rho_3 A_{43F}]$$

Combined Exit Coupled Motion Differential Equation with Mesh No. 2 in Round-on-Flat Contact

Equations D-339 and D-395 are now set equal to each other in order to obtain the combined coupled motion differential equation of the escapement under exit conditions

$$[AA_{51F}I_{PR}U - AA_{29}I_{zs}]\ddot{\phi} + [AA_{51F}(A_{32}U^2 + I_{PR}V) - AA_{29}A_{48F}]\dot{\phi}^2$$

$$+ AA_{51F}A_{31}U\dot{\phi} = F_{23F}AA_{29}A_{49F} + AA_{29}A_{50F} - AA_{51F}(A_9 + A_{30})$$

$$+ AA_{51F}m_p r_{cp}(K_x \sin\beta - K_y \cos\beta) \qquad \text{(D-397)}$$

The above expression has the same form as equation D-327, and the difference between entrance and exit coupled motion depends, as for the round-on-round regimes, on the value of the signum function s_7, as defined in preceding equation D-367.

Common Differential Equation and Common Expressions for Entrance and Exit Coupled Motion of the Escapement with Mesh No. 2 in Round-on-Flat Contact

Just as for round-on-round contact of mesh no. 2 (eq D-372) it is possible, with the help of signum functions s_7, to obtain certain expressions that are common to both entrance and exit coupled motion differential equations for the combined escapement when mesh no. 2 is in round-on-flat contact.

Since the resulting expressions depend only on the escapement geometry, they are not influenced by the type of contact of mesh no. 2, and they are, therefore, identical to those indicated earlier in equations D-367 to D-371c.

The follwing enumerates these parameters with the appropriate change of the relevant subscriptions.

As in equation D-367, D-54 and D-333 are combined to

$$A_{16} = AA_{16} = -\left[\mu_1 s_4 \cos(\psi + \alpha) - s_7 \sin(\psi + \alpha)\right] \qquad \text{(D-398)}$$

Again, as in equation D-368, D-60 and D-334 have the common form

$$A_{21} = AA_{21} = -\left[s_7 \cos(\psi + \alpha) + \mu_1 s_4 \sin(\psi + \alpha)\right] \qquad \text{(D-399)}$$

Because of the above general expressions, the expressions for C_5, C_{10}, C_{15}, and C_{20} (eqs D-86, D-96, D-106, and D-116, respectively) which are functions of them, can be used to determine the identical forms of A_{28} and AA_{28} (eqs D-122a and D-336, respectively).

$$A_{29} = AA_{29} = s_7 D_1' - C_1' \mu_1 s_4 - \rho_P \mu_1 s_5 A_{28} \qquad \text{(D-400)}$$

As in equation D-370, equations D-177 and D-348, as well as D-261 and D-379, will be satisfied with

$$A_{33} = A_{33R} = AA_{33R} = A_{33F} = AA_{33F} = \mu_1 s_4 \cos\left(\psi + \alpha + \beta_3\right)$$

$$- s_7 \sin\left(\psi + \alpha + \beta_3\right) \qquad \text{(D-401)}$$

Also, as in equation D-371a, equations D-181 and D-349, as well as D-265 and D-380 will be satisfied with

$$A_{36} = A_{36R} = AA_{36R} = A_{36F} = AA_{36F} = \mu_1 s_4 \sin\left(\psi + \alpha + \beta_3\right)$$

$$+ s_7 \cos\left(\psi + \alpha + \beta_3\right) \qquad \text{(D-204a)}$$

Because of the generality of A_{33} and A_{36}. the following parameters which are functions of A_{33} and A_{36}, also only depend on s_7 and common expressions may be found.

$$\left.\begin{array}{l} C_{22} = C_{22R} = CC_{22R} = C_{22F} = CC_{22F} \text{ (eqs D-201, D-352, D-285, D-384, resp)} \\ C_{26} = C_{26R} = CC_{26R} = C_{26F} = CC_{26F} \text{ (eqs D-209, D-355, D-293, D-386, resp)} \\ C_{30} = C_{30R} = CC_{30R} = C_{30F} = CC_{30F} \text{ (eqs D-217, D-357, D-301, D-388, resp)} \\ C_{34} = C_{34R} = CC_{34R} = C_{34F} = CC_{34F} \text{ (eqs D-225, D-359, D-309, D-390, resp)} \end{array}\right\} \text{(D-402b)}$$

The above now leads to

$$A_{44} = A_{44R} = AA_{44R} = A_{44F} = AA_{44F} = \frac{C_{22} + C_{26} + C_{30} + C_{34}}{L_T\left(1 + \mu^2\right)} \qquad \text{(D-402c)}$$

with equations D-231, D-361, D-315, and D-392, respectively.

Finally, as in equation D-371b, equations D-243 and D-365, as well as D-326 and D-396 will be satisified with

$$A_{51} = A_{51R} = AA_{51R} = A_{51F} = AA_{51F} = B_1' \mu_1 s_4 - s_7 A_1' - \mu \rho_3 A_{44} \qquad \text{(D-402d)}$$

These considerations now make it possible to write a combined escapement differential equation for coupled motion when mesh no. 2 is in round-on-flat contact

$$[A_{51} I_{PR} U - A_{29} I_{zs}]\ddot{\phi} + [A_{51}(A_{32}U^2 + I_{PR}V) - A_{29}A_{48}]\dot{\phi}^2 + A_{51}A_{31}U\dot{\phi}$$

$$= F_{23F}A_{29}A_{49F} + A_{29}A_{50} - A_{51}(A_9 + A_{30}) + A_{51}m_P r_{cp}(K_x \sin\beta - K_y \cos\beta) \quad \text{(D-403)}$$

Note the similarity of the above expression with equation D-372. It differs only in the parameters F_{23F} and A_{49F}. The letter subscripts of A_{48} and A_{50} have again been dropped, since these parameters depend only on mass and friction.

DYNAMICS OF ROTOR AND GEAR NO. 1

Before the force and moment equations of the rotor, with mesh no. 1 in round-on-round or round-on-flat contact, can be considered, it is first necessary to obtain expressions for the absolute acceleration of the rotor pivot 0_1 and the rotor center of mass C_1.

A top view of the rotor in the mechanism plane is shown in figure D-10. (fig. A-3).

Absolute Acceleration of Rotor Pivot O_1

The absolute acceleration of the rotor pivot 0_1 is given by

$$\overline{A}_{O_1/ground} = \overline{A}_{O_1/C} + \overline{A}_{C/ground} \quad \text{(D-404)}$$

where

$A_{C/ground}$ = given by equation C-4, appendix C in the projectile fixed X-Y system,

while

$$\overline{A}_{O_1/C} = \overline{\omega} \times (\overline{\omega} \times \overline{\Re}_1) + \dot{\overline{\omega}} \times \overline{\Re}_1 \quad \text{(D-405)}$$

After substituting

$$\bar{\Re}_1 = \Re_1 \bar{i} \tag{D-406}$$

and equations A-1 and A-5 for ϖ and $\dot{\bar{\omega}}$, respectively, the following is obtained

$$\bar{A}_{O_1/C} = L_x \bar{i} + L_y \bar{j} + L_z \bar{k} \tag{D-407}$$

where

$$L_x = -(\omega_y^2 + \omega_z^2)\,\Re_1 \tag{D-408}$$

$$L_y = (\omega_x \omega_y + \dot{\omega}_z)\Re_1 \tag{D-409}$$

$$L_z = (\omega_x \omega_z - \dot{\omega}_y)\Re_1 \tag{D-410}$$

Together with equations D-87 and C-4, the following is obtained for equation D-404

$$\bar{A}_{O_1/ground} = O_x \bar{i} + O_y \bar{j} + O_z \bar{k} \tag{D-411}$$

where

$$O_x = G_x + L_x \tag{D-412}$$

$$O_y = G_y + L_y \tag{D-413}$$

$$O_z = G_z + L_z \tag{D-414}$$

Absolute Acceleration of the Rotor Center of Mass C_1

To determine the absolute acceleration of the rotor center of mass in the X-Y-Z system, it is first necessary to find $\bar{A}_{C_1/O_1}$, the acceleration of the rotor center of mass with respect to the rotor pivot O_1, in the ξ_1 - η_1 - ζ_1 system (fig. D-10). Subsequently, this expression is transformed into the X-Y-Z system and added to the absolute acceleration of point O_1 as given by equation D-411. Therefore

$$\bar{A}_{C_1/ground} = \bar{A}_{C_1/O_1} + \bar{A}_{O_1/ground} \tag{D-415}$$

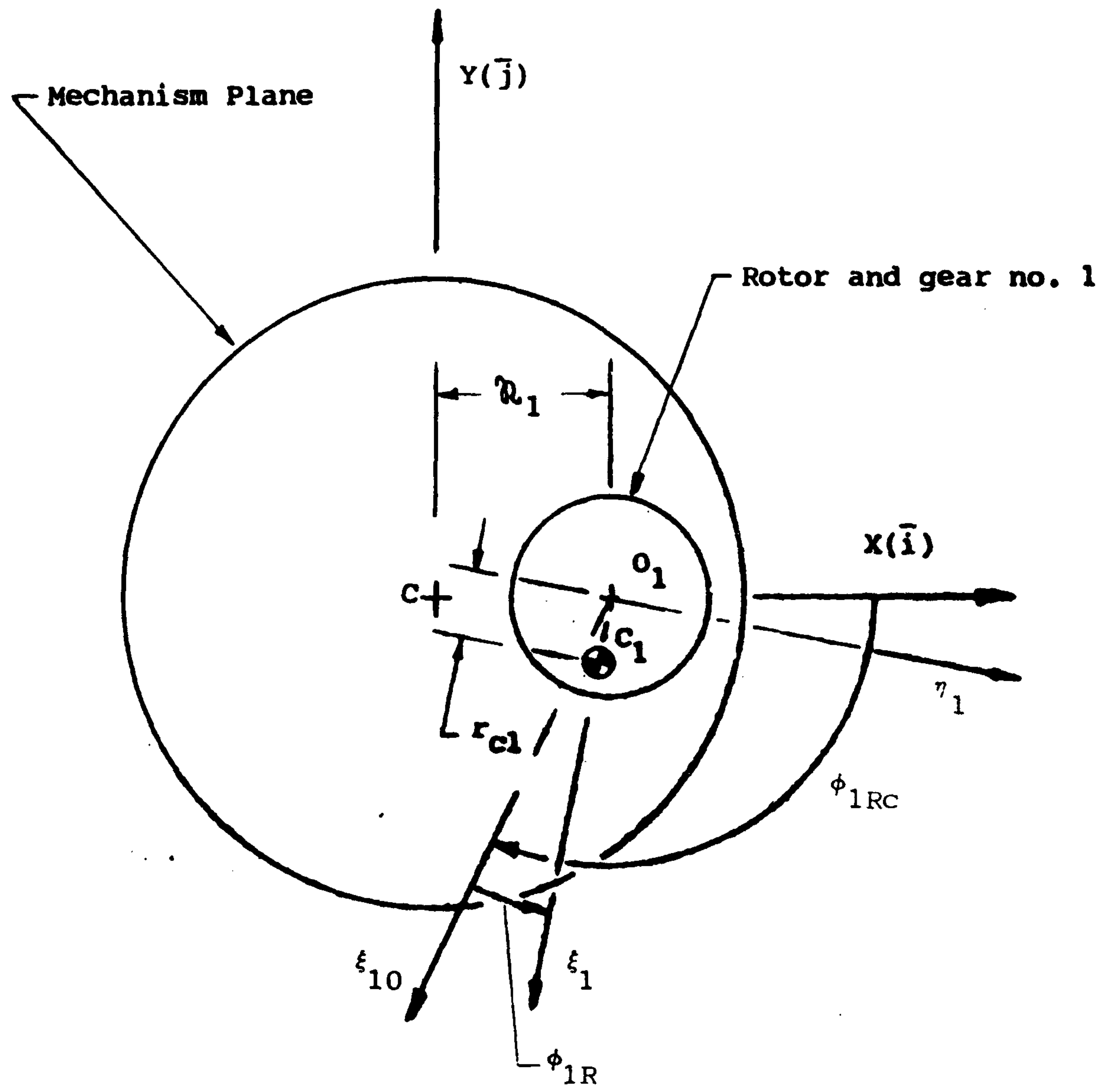


Figure D-10. Top view of rotor and gear no. 1 and mechanism plane

The term $\bar{A}_{C_1/O_1}$ is obtained from

$$\bar{A}_{C_1/O_1} = \bar{\omega}_1 \times (\bar{\omega}_1 \times \bar{r}_{c1}) + \dot{\bar{\omega}}_1 \times \bar{r}_{c1} \tag{D-416}$$

where

$$\bar{r}_{c1} = r_{c1}\,\bar{n}_{\xi_1} \tag{D-417}$$

The terms $\bar{\omega}_1$ and $\dot{\bar{\omega}}_1$ are taken from equations A-37 and A-41, respectively.

When all operations are performed, equation D-416 becomes

$$\bar{A}_{C_1/O_1} = -\,r_{C1}\left[\omega_{\eta_1}^2 + \omega_{\zeta_1}^2\right]\bar{n}_{\xi_1} + r_{C1}\left[\omega_{\xi_1}\omega_{\eta_1} + \dot{\omega}_{\zeta_1}\right]\bar{n}_{\eta_1} + r_{C1}\left[\omega_{\xi_1}\omega_{\zeta_1} - \dot{\omega}_{\eta_1}\right]\bar{n}_{\zeta_1} \tag{D-418}$$

With the help of equations A-31 to A-34 substitute for the above body-fixed unit vectors; i.e.

$$\bar{n}_{\xi_1} = \cos\gamma\,\bar{i} + \sin\gamma\,\bar{j} \tag{D-419}$$

$$\bar{n}_{\eta_1} = -\sin\gamma\,\bar{i} + \cos\gamma\,\bar{j} \tag{D-420}$$

$$\bar{n}_{\zeta_1} = \bar{k} \tag{D-421}$$

where

$$\gamma = \phi_{1Rc} + \phi_{1R} \tag{D-422}$$

This results in

$$\bar{A}_{C_1/O_1} = -r_{c1}[(\omega_{\eta_1}^2 + \omega_{\zeta_1}^2)\cos\gamma + (\omega_{\xi_1}\omega_{\eta_1} + \dot{\omega}_{\zeta_1})\sin\gamma]\,\bar{i} - r_{c1}\,[(\omega_{\eta_1}^2 + \omega_{\zeta_1}^2)$$

$$\sin\gamma - (\omega_{\xi_1}\omega_{\eta_1} + \dot{\omega}_{\zeta_1})\cos\gamma]\,\bar{j} + r_{c1}(\omega_{\xi_1}\omega_{\zeta_1} - \dot{\omega}_{\eta_1})\,\bar{k} \tag{D-423}$$

Finally, equations A-38 to A-40 and A-42 to A-44 are used to express the angular quantities

$$\bar{A}_{C_1/O_1} = -r_{c1}\{[(\omega_y^2 \cos\gamma - \omega_x\omega_y \sin\gamma + (\omega_z + \dot{\phi}_1)^2 \cos\gamma + (\dot{\omega}_z + \ddot{\phi}_1)\sin\gamma]\,\bar{i}$$

$$+ [\omega_x^2 \sin\gamma - \omega_x\omega_y \cos\gamma + (\omega_z + \dot{\phi}_1)^2 \sin\gamma - (\dot{\omega}_z + \ddot{\phi}_1)\cos\gamma]\,\bar{j}$$

$$- [(\omega_x \cos\gamma + \omega_y \sin\gamma)(\omega_z + 2\dot{\phi}_1) + \dot{\omega}_x \sin\gamma - \dot{\omega}_y \cos\gamma]\,\bar{k}\} \qquad \text{(D-424)}$$

The total acceleration $A_{C_1/ground}$ then becomes according to equation D-415 with equation D-411

$$\bar{A}_{C_1/ground} = \{-r_{c1}[\omega_y^2 \cos\gamma - \omega_x\omega_y \sin\gamma + (\omega_z + \dot{\phi}_1)^2 \cos\gamma + (\dot{\omega} + \ddot{\phi}_1)\sin\gamma] + O_x\}\,\bar{i}$$

$$+ \{-r_{c1}[\omega_x^2 \sin\gamma - \omega_x\omega_y \cos\gamma + (\omega_z + \dot{\phi}_1)^2 \sin\gamma - (\dot{\omega}_z + \ddot{\phi}_1)\cos\gamma] + O_y\}\,\bar{j}$$

$$+ \{r_{c1}[(\omega_x \cos\gamma + \omega_y \sin\gamma)(\omega_z + 2\dot{\phi}_1) + \dot{\omega}_x \sin\gamma - \dot{\omega}_y \cos\gamma] + O_z\}\,\bar{k} \qquad \text{(D-425)}$$

It must be kept in mind that the angle ϕ_{1R} depends on the total rotational angle ϕ_T of the escape wheel. Because of the clock gearing involved, its value cannot be obtained by a constant gear ratio as for involute gearing, but must be determined from the incremental changes in the two meshes, which depend on the contact modes involved.

The angular velocity $\dot{\phi}_1$ and the angular acceleration $\ddot{\phi}_1$ must be expressed in terms of the escape wheel angular velocity $\dot{\phi}$ and the escape wheel angular acceleration $\ddot{\phi}$, respectively. Appendix F gives closed form expressions for these quantities. They are dependent on whichever of the four possible contact modes of the two meshes governs.

Mesh No. 1 in Round-On-Round Contact

Force Equations for the Rotor and Gear No. 1 With Mesh No. 1 in Round-On-Round Contact

A top view of the rotor and gear no. 1, together with the mechanism plane, is shown in figure D-11a. It indicates the round-on-round contact force $\bar{F}_{21}$ as well as the associated friction force $\bar{F}_{f12}$. Thus, (ref 5) with both forces equal to and opposite to $\bar{F}_{12}$ and F_{f12}, of equations D-611 and D-612, respectively

$$\bar{F}_{21} = -F_{12}\bar{n}_{\lambda 1} \qquad \text{(D-426)}$$

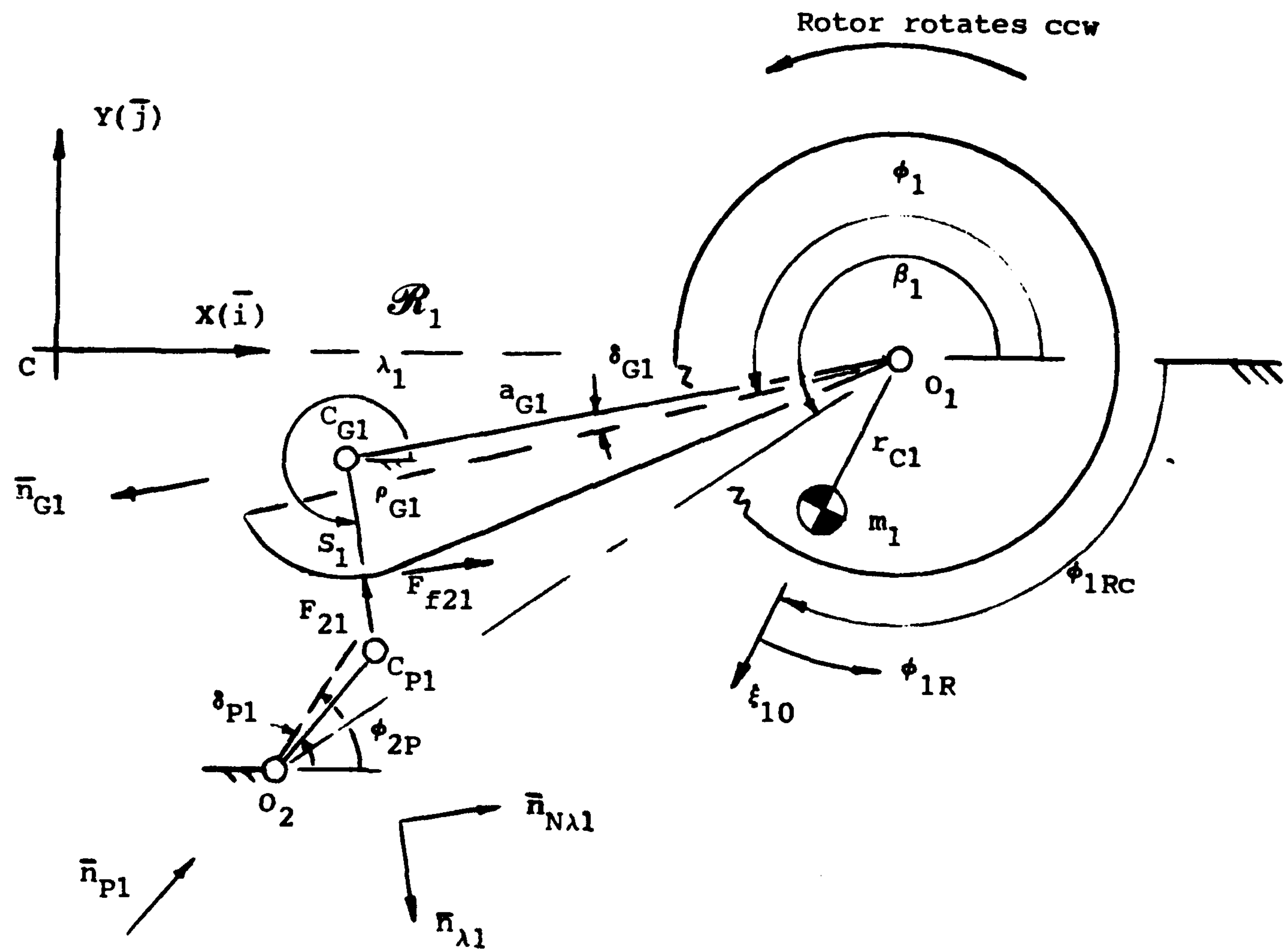


Figure D-11a. Top view of free body diagram of rotor and gear no. 1. Mesh no. 1 is in round-on-round contact.

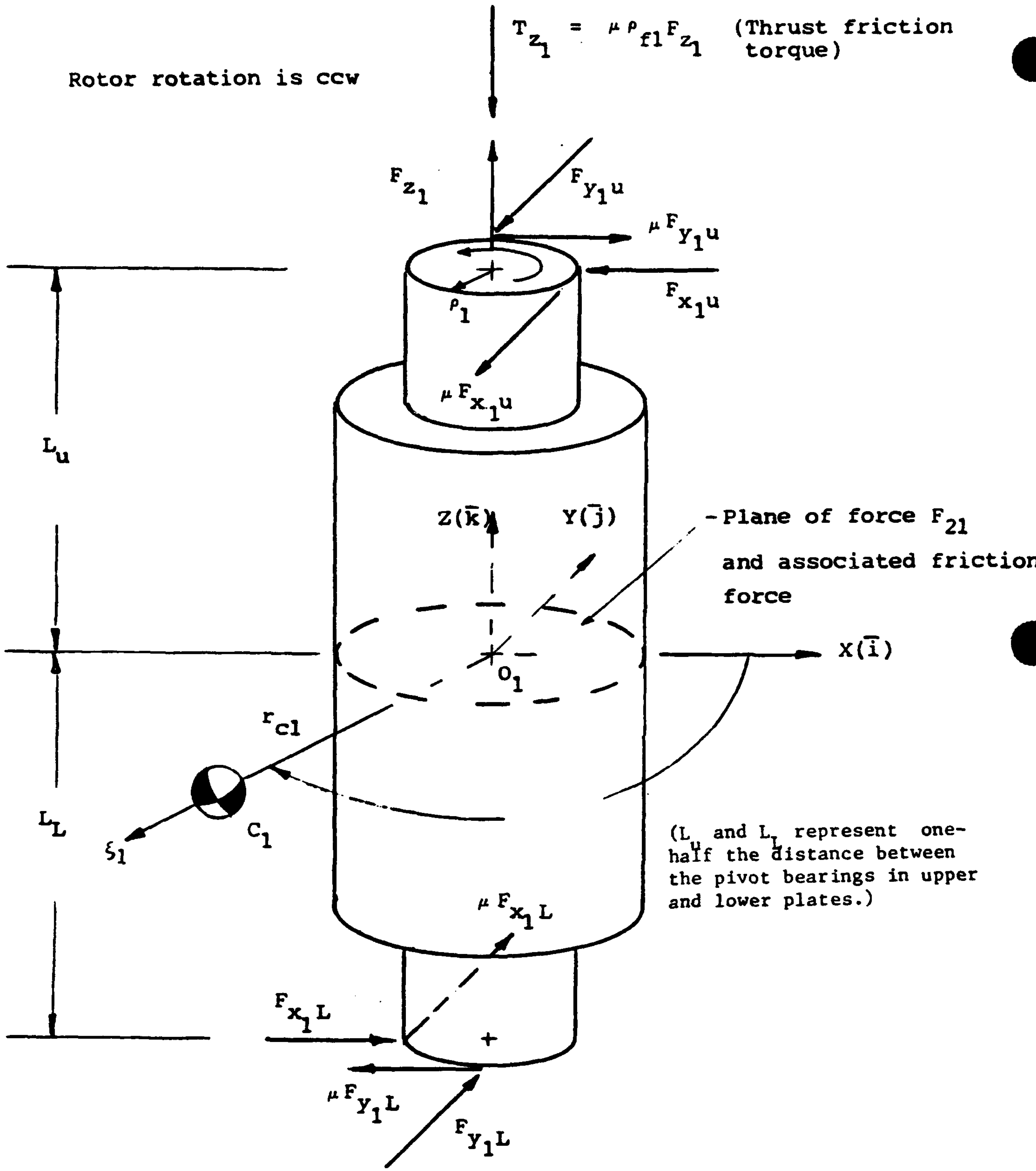


Figure D-11b. Rotor and gear no. 1. Normal forces, friction forces, and thrust friction torque acting on rotor pivots. (Not influenced by type of mesh contact.)

where, according to equation G-2 of reference 5

$$\bar{n}_{\lambda 1} = \cos\lambda_1 \bar{i} + \sin\lambda_1 \bar{j} \qquad \text{(D-427)}$$

Further,

$$\bar{F}_{f21} = -\mu s_{1R} F_{12} \bar{n}_{N\lambda 1} \qquad \text{(D-428)}$$

where, according to equation G-3 of reference 5

$$\bar{n}_{N\lambda 1} = -\sin\lambda_1 \bar{i} + \cos\lambda_1 \bar{j} \qquad \text{(D-429)}$$

and, with the help of equation G-21, reference 5, the signum function s_{1R} is defined as (equation F-13, app F).

$$S_{1R} = \frac{V_{S_1/T_{1_R}}}{|V_{S_1/T_{1_R}}|} \qquad \text{(D-430)}$$

A free body diagram of the rotor pivot with all normal and friction forces is shown in figure D-11b.

The force equation for the rotor is given by

$$\Sigma \bar{F} = m_1 \bar{A}_{C_1/\text{ground}} \qquad \text{(D-431)}$$

where $\bar{A}_{C_1/\text{ground}}$ is given by equation D-425. Therefore

$$-F_{12}\bar{n}_{\lambda 1} - \mu s_{1R} F_{12}\bar{n}_{N\lambda 1} + F_{z1}\bar{k} - F_{x1u}\bar{i} - F_{y1u}\bar{j} - \mu F_{x1u}\bar{j} + \mu F_{y1u}\bar{i}$$

$$+ F_{x1L}\bar{i} + F_{y1L}\bar{i} + \mu F_{x1L}\bar{j} - \mu F_{y1L}\bar{i} = m_1 \bar{A}_{C_1/\text{ground}} \qquad \text{(D-432)}$$

The unit vectors of equations D-427 and D-429 are now substituted into equation D-432. Subsequently, the component expressions of this equation are written with the help of equation D-425

X-Component of Rotor Force Equation

$$- F_{12}\cos\lambda_1 + \mu s_{1R} F_{12}\sin\lambda_1 - F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L} = m_1 [-r_{C1}$$

$$\{\omega_y^2 \cos\gamma - \omega_x\omega_y \sin\gamma + (\omega_z + \dot{\phi}_1)^2 \cos\gamma + (\dot{\omega}_z + \ddot{\phi}_1) \sin\gamma\} + O_x] \qquad \text{(D-433)}$$

Y-Component of Rotor Force Equation

$$-F_{12}\sin\lambda_1 - \mu s_{1R}F_{12}\cos\lambda_1 - F_{y1u} - \mu F_{x1u} + F_{y1L} + \mu F_{x1L} = m_1\left[-r_{c1}\right.$$

$$\left.\left\{\omega_x^2\sin\gamma - \omega_x\omega_y\cos\gamma + \left(\omega_z + \dot{\phi}_1\right)^2\sin\gamma - \left(\dot{\omega}_z + \ddot{\phi}_1\right)\cos\gamma\right\} + O_y\right] \qquad \text{(D-434)}$$

Z-Component of Rotor Force Equation

$$F_{z1} = m_1\left\{r_{c1}\left[\left(\omega_x\cos\gamma + \omega_y\sin\gamma\right)\left(\omega_z + 2\dot{\phi}_1\right) + \dot{\omega}_x\sin\gamma - \dot{\omega}_y\cos\gamma\right] + O_z\right\} \qquad \text{(D-435)}$$

Moment Equations for the Rotor and Gear No. 1 With Mesh 1 in Round-On-Round Contact

The moment equation for the rotor must be written with respect to the accelerated pivot point O_1. (This is similar to the manner in which the pallet moment expression D-3c was written with respect to point O_p.) Therefore

$$\overline{M}_{O_1} = \overline{A}_{O_1/\text{ground}} \times m_1 r_{c1}\left(\cos\gamma\bar{i} + \sin\gamma\bar{j}\right) + \dot{\overline{H}}_{O_1} \qquad \text{(D-436)}$$

where

$\overline{M}_{O_1}$ = sum of external moments about point O_1. It is assumed that O_1 lies in the plane of the rotor cen of mass, and that F_{12} and $\mu s_{1R}F_{12}$ also lie in this plane.

$\overline{A}_{O_1/\text{ground}}$ = absolute acceleration of point O_1 (eq. D411).

$\dot{\overline{H}}_{O_1}$ = time rate of change of angular momentum of rotor with respect to point O_1.

It is obtained by adapting equation B-4 of appendix B to the $\xi_1 - \eta_1 - \zeta_1$ system. The appropriate angular velocity and acceleration components are given by equations A-37 and A-41, respectively. The transformation into the X-Y-Z system is accomplished with the help of the unit vector expressions of equations D-419 to D-421.

Determination of $\overline{M}_{O_1}$. The moment $\overline{M}_{F21}$ of the contact force $\overline{F}_{21}$ with respect to pivot O_1 is given by

$$\overline{M}_{F21} = (a_{G1}\overline{n}_{G1} + \rho_{G1}\overline{n}_{\lambda 1}) \times (F_{12}\overline{n}_{\lambda 1} - \mu s_{1R}F_{12}\overline{n}_{N\lambda 1}) \qquad \text{(D-437)}$$

This becomes, with the help of equations D-423 and D-425, as well as with

$$\overline{n}_{G1} = \cos(\phi_1 - \delta_{G1})\,\overline{i} + \sin(\phi_1 - \delta_{G1})\,\overline{j} \qquad \text{(D-438)}$$

as obtained from equation G-1 reference 5.

$$\overline{M}_{F21} = a_{G1}F_{12}\left[\sin(\phi_1 - \delta_{G1} - \lambda_1) - \mu s_{1R}\cos(\phi_1 - \delta_{G1} - \lambda_1)\right]\overline{k} - \mu s_{1R}\rho_{G1}F_{12}\overline{k} \qquad \text{(D-439)}$$

In addition to the above, the moments due to the various pivot forces may be adapted from equation D-32. Since the rotor always has counter-clockwise rotation, let $s_5 = +1$ in equation D-32. Further, change μ_1 to μ, and adjust the subscripts from the primed to the unprimed coordinate system. Finally, with equation D-439 one obtains for the moments with respect to pivot O_1

$$\begin{aligned}\overline{M}_{O_1} = &\left[L_uF_{y1u} + \mu L_uF_{x1u} + L_LF_{y1L} + \mu L_LF_{x1L}\right]\overline{i} + \left[\mu L_uF_{y1u} - L_uF_{x1u}\right.\\ &\left.+ \mu L_LF_{y1L} - L_LF_{x1L}\right]\overline{j} + \left[a_{G1}F_{12}\left\{\sin(\phi_1 - \delta_{G1} - \lambda_1) - \mu s_{1R}\cos(\phi_1 - \delta_{G1} - \lambda_1)\right\}\right.\\ &\left.- \mu s_{1R}\rho_{G1}F_{12} - \mu\rho_{f1}\widetilde{F}_{z1} - \rho_1\mu F_{y1u} - \rho_1\mu F_{x1u} - \rho_1\mu F_{y1L} - \rho_1\mu F_{x1L}\right]\overline{k}\end{aligned} \qquad \text{(D-440)}$$

Note the tilded form of $\widetilde{F}_{z1}$, which will be explained by equation D-474.

Determination of First Term on Right Hand Side of Equation D-436. With the help of equation D-411, the following is obtained for the right hand side of equation D-436

$$-(O_x\bar{i} + O_y\bar{j} + O_z\bar{k}) \times m_1 r_{c1}(\cos\gamma\bar{i} + \sin\gamma\bar{j}) = m_1 r_{c1}[O_z\sin\gamma\bar{i} - O_z\cos\gamma\bar{j}$$

$$- (O_x\sin\gamma - O_y\cos\gamma)\bar{k}] \qquad \text{(D-441)}$$

Determination of Time Rate of Change of Angular Momentum with Respect to Rotor Pivot O_1. To obtain an expression for $\dot{\bar{H}}_{O_1}$ in the $\xi_1 - \eta_1 - \zeta_1$ rotor-fixed system, equation B-4 is first adapted from the X-Y-Z system. Subsequently, the angular velocity and acceleration of equations A-37 and A-41 are substituted as follows

$$\omega_{\xi_1} = \omega_x\cos\gamma + \omega_y\sin\gamma \qquad \text{(D-442)}$$

$$\omega_{\eta_1} = -\omega_x\sin\gamma + \omega_y\cos\gamma \qquad \text{(D-443)}$$

$$\omega_{\zeta_1} = \omega_z + \dot{\phi}_1 \qquad \text{(D-444)}$$

$$\dot{\omega}_{\xi_1} = \dot{\omega}_x\cos\gamma - \omega_x\dot{\phi}_1\sin\gamma + \dot{\omega}_y\sin\gamma + \omega_y\dot{\phi}_1\cos\gamma \qquad \text{(D-445)}$$

$$\dot{\omega}_{\eta_1} = -\dot{\omega}_x\sin\gamma - \omega_x\dot{\phi}_1\cos\gamma + \dot{\omega}_y\cos\gamma - \omega_y\dot{\phi}_1\sin\gamma \qquad \text{(D-446)}$$

$$\dot{\omega}_{\zeta_1} = \dot{\omega}_z + \ddot{\phi}_1 \qquad \text{(D-447)}$$

Finally, the body-fixed unit vectors $\bar{n}_{\xi_1}$, $\bar{n}_{\eta_1}$, and $\bar{n}_{\zeta_1}$ are given in the X-Y-Z system according to equations D-419 to D-421. This furnishes

$$
\begin{aligned}
\bar{H}_{O_1} = {} & \{I_{\xi\xi_1}(\dot{\omega}_x\cos\gamma - \omega_x\dot{\phi}_1\sin\gamma + \dot{\omega}_y\sin\gamma + \omega_y\dot{\phi}_1\cos\gamma) + (-\omega_x\sin\gamma - \omega_y\cos\gamma) \\
& (\omega_z + \dot{\phi}_1)(I_{\zeta\zeta_1} - I_{\eta\eta_1}) + I_{\xi\eta_1}[(\omega_z + \dot{\phi}_1)(\omega_x\cos\gamma + \omega_y\sin\gamma) - (-\dot{\omega}_x\sin\gamma - \omega_x\dot{\phi}_1\cos\gamma \\
& + \dot{\omega}_y\cos\gamma - \omega_y\dot{\phi}_1\sin\gamma)] - I_{\xi\zeta_1}[(\omega_x\cos\gamma + \omega_y\sin\gamma)(-\omega_x\sin\gamma + \omega_y\cos\gamma)(\dot{\omega}_z + \ddot{\phi}_1)] - I_{\eta\zeta_1} \\
& [(-\omega_x\sin\gamma + \omega_y\cos\gamma)^2 - (\omega_z + \dot{\phi}_1)^2]\}(\cos\gamma\bar{i} + \sin\gamma\bar{j}) + \{I_{\eta\eta_1}(-\dot{\omega}_x\sin\gamma - \omega_x\dot{\phi}_1\cos\gamma \\
& + \dot{\omega}_y\cos\gamma - \omega_y\dot{\phi}_1\sin\gamma) + (\omega_x\cos\gamma + \omega_y\sin\gamma)(\omega_z + \dot{\phi}_1)(I_{\xi\xi_1} - I_{\zeta\zeta_1}) + I_{\eta\zeta_1}[(\omega_x\cos\gamma \\
& + \omega_y\sin\gamma)(-\omega_x\sin\gamma + \omega_y\cos\gamma) - (\dot{\omega}_z + \ddot{\phi}_1)] - I_{\xi\eta_1}[(\dot{\omega}_x\cos\gamma - \omega_x\dot{\phi}_1\sin\gamma + \dot{\omega}_y\sin\gamma \\
& + \omega_y\dot{\phi}_1\cos\gamma) + (-\omega_x\sin\gamma + \omega_y\cos\gamma)(\omega_z + \dot{\phi}_1) - I_{\xi\zeta_1}[(\omega_z + \dot{\phi}_1)^2 - (\omega_x\cos\gamma + \omega_y\sin\gamma)^2]\} \\
& (-\sin\gamma\bar{i} + \cos\gamma\bar{j}) + \{I_{\zeta\zeta_1}(\dot{\omega}_z + \ddot{\phi}_1) + (\omega_x\cos\gamma + \omega_y\sin\gamma)(-\omega_x\sin\gamma + \omega_y\cos\gamma) \times (I_{\eta\eta_1} \\
& - I_{\xi\xi_1}) + I_{\zeta\xi_1}[(-\omega_x\sin\gamma + \omega_y\cos\gamma)(\omega_z + \dot{\phi}_1) - (\dot{\omega}_x\cos\gamma - \omega_x\dot{\phi}_1\sin\gamma + \dot{\omega}_y\sin\gamma \\
& + \omega_y\dot{\phi}_1\cos\gamma)] - I_{\zeta\eta_1}[(-\dot{\omega}_x\sin\gamma - \omega_x\dot{\phi}_1\cos\gamma + \dot{\omega}_y\cos\gamma - \omega_y\dot{\phi}_1\sin\gamma) + (\omega_x\cos\gamma + \omega_y\sin\gamma) \\
& (\omega_z + \dot{\phi}_1)] - I_{\xi\eta_1}[(\omega_x\cos\gamma + \omega_y\sin\gamma)^2 - (-\omega_x\sin\gamma + \omega_y\cos\gamma)^2]\}\bar{k} \qquad \text{(D-448)}
\end{aligned}
$$

The components $\dot{H}_{O_{1x}}$, $\dot{H}_{O_{1y}}$, and $\dot{H}_{O_{1z}}$ must now be determined from equation D-448. This leads to

$$\dot{H}_{O_{1x}} = A_{52} + A_{53}\dot{\phi}_1 + A_{54}\dot{\phi}_1^2 + A_{55}\ddot{\phi}_1 \qquad \text{(D-449)}$$

where

$$A_{52} = \cos\gamma\{I_{\xi\xi_1}(\dot{\omega}_x\cos\gamma + \dot{\omega}_y\sin\gamma) + (I_{\zeta\zeta_1} - I_{\eta\eta_1})\,\omega_z(-\omega_x\sin\gamma - \omega_y\cos\gamma) + I_{\xi\eta_1}$$

$$[\omega_z(\omega_x\cos\gamma + \omega_y\sin\gamma) + (\dot{\omega}_x\sin\gamma - \dot{\omega}_y\cos\gamma)] - I_{\xi\zeta_1}[(\omega_x\cos\gamma + \omega_y\sin\gamma)(-\omega_x\sin\gamma$$

$$+ \omega_y\cos\gamma) + \dot{\omega}_z] - I_{\eta\zeta_1}[(-\omega_x\sin\gamma + \omega_y\cos\gamma)^2 - \omega_z^2]\} - \sin\gamma\{I_{\eta\eta_1}(-\dot{\omega}_x\sin\gamma$$

$$+ \dot{\omega}_y\cos\gamma) + (I_{\xi\xi_1} - I_{\zeta\zeta_1})\,\omega_z(\omega_x\cos\gamma + \omega_y\sin\gamma) + I_{\eta\zeta_1}[(\omega_x\cos\gamma + \omega_y\sin\gamma)(-\omega_x\sin\gamma$$

$$+ \omega_y\cos\gamma) - \dot{\omega}_z] - I_{\xi\eta_1}[(\dot{\omega}_x\cos\gamma + \dot{\omega}_y\sin\gamma) + \omega_z(-\omega_x\sin\gamma + \omega_y\cos\gamma)] - I_{\xi\zeta_1}$$

$$[\omega_z^2 - (\omega_x\cos\gamma + \omega_y\sin\gamma)^2]\} \qquad \text{(D-450)}$$

$$A_{53} = [-\omega_x\sin\gamma + \omega_y\cos\gamma][(I_{\xi\xi_1} + I_{\zeta\zeta_1} - I_{\eta\eta_1})\cos\gamma + 2I_{\xi\eta_1}\sin\gamma] + [\omega_x\cos\gamma$$

$$+ \omega_y\sin\gamma][(I_{\eta\eta_1} - I_{\xi\xi_1} + I_{\zeta\zeta_1})\sin\gamma + 2I_{\xi\eta_1}\cos\gamma] + 2\omega_z[I_{\eta\xi_1}\cos\gamma + I_{\xi\zeta_1}\sin\gamma] \qquad \text{(D-451)}$$

$$A_{54} = I_{\eta\xi_1}\cos\gamma + I_{\xi\zeta_1}\sin\gamma \qquad \text{(D-452)}$$

$$A_{55} = -I_{\xi\zeta_1}\cos\gamma + I_{\eta\zeta_1}\sin\gamma \qquad \text{(D-453)}$$

Further

$$\dot{H}_{O_{1y}} = A_{56} + A_{57}\dot{\phi}_1 + A_{58}\dot{\phi}_1^2 + A_{59}\ddot{\phi}_1 \qquad \text{(D-454)}$$

$$A_{56} = \sin\gamma\{I_{\xi\xi_1}(\dot{\omega}_x\cos\gamma + \dot{\omega}_y\sin\gamma) + (I_{\zeta\zeta_1} - I_{\eta\eta_1})(-\omega_x\sin\gamma + \omega_y\cos\gamma)\,\omega_z + I_{\xi\eta_1}$$

$$[\omega_z(\omega_x\cos\gamma + \omega_y\sin\gamma) - (-\dot{\omega}_x\sin\gamma + \dot{\omega}_y\cos\gamma)] - I_{\xi\zeta_1}[(\omega_x\cos\gamma + \omega_y\sin\gamma)(-\omega_x\sin\gamma$$

$$+ \omega_y\cos\gamma) + \dot{\omega}_z] - I_{\eta\zeta_1}[(-\omega_x\sin\gamma + \omega_y\cos\gamma)^2 - \omega_z^{\ 2}]\} + \cos\gamma\{I_{\eta\eta_1}(-\dot{\omega}_x\sin\gamma$$

$$+ \dot{\omega}_y\cos\gamma) + (I_{\xi\xi_1} - I_{\zeta\zeta_1})(\omega_x\cos\gamma + \omega_y\sin\gamma)\omega_z + I_{\eta\zeta_1}[(\omega_x\cos\gamma + \omega_y\sin\gamma)(-\omega_x\sin\gamma$$

$$+ \omega_y\cos\gamma) - \dot{\omega}_z] - I_{\xi\eta_1}[\dot{\omega}_x\cos\gamma + \dot{\omega}_y\sin\gamma + \omega_z(-\omega_x\sin\gamma + \omega_y\cos\gamma)] - I_{\xi\zeta_1}$$

$$[\omega_z^{\ 2} - (\omega_x\cos\gamma + \omega_y\sin\gamma)^2]\} \qquad \text{(D-455)}$$

$$A_{57} = [-\omega_x\sin\gamma + \omega_y\cos\gamma] \times [(I_{\xi\xi_1} + I_{\zeta\zeta_1} - I_{\eta\eta_1})\sin\gamma - 2I_{\xi\eta_1}\cos\gamma] + [\omega_x\cos\gamma$$

$$+ \omega_y\sin\gamma] \times [2I_{\xi\eta_1}\sin\gamma + (I_{\xi\xi_1} - I_{\zeta\zeta_1} - I_{\eta\eta_1})\cos\gamma] + 2\omega_z[I_{\eta\zeta_1}\sin\gamma - I_{\xi\zeta_1}\cos\gamma] \qquad \text{(D-456)}$$

$$A_{58} = I_{\eta\zeta_1}\sin\gamma - I_{\xi\zeta_1}\cos\gamma \qquad \text{(D-457)}$$

$$A_{59} = -[I_{\xi\zeta_1}\sin\gamma + I_{\eta\zeta_1}\cos\gamma] \qquad \text{(D-458)}$$

Finally

$$\dot{H}_{O_{1z}} = A_{60} + A_{61}\ddot{\phi}_1 \qquad \text{(D-459)}$$

where

$$A_{60} = I_{\zeta\zeta_1}\dot{\omega}_z + (I_{\eta\eta_1} - I_{\xi\xi_1})(\omega_x \cos\gamma + \omega_y \sin\gamma) \times (-\omega_x \sin\gamma + \omega_y \cos\gamma) + I_{\zeta\xi_1}$$

$$[(-\omega_x \sin\gamma + \omega_y \cos\gamma)\omega_z - \dot{\omega}_x \cos\gamma - \dot{\omega}_y \sin\gamma] + I_{\zeta\eta_1}[\dot{\omega}_x \sin\gamma - \dot{\omega}_y \cos\gamma - \omega_z$$

$$(\omega_x \cos\gamma + \omega_y \sin\gamma)] - I_{\xi\eta_1}[(\omega_x \cos\gamma + \omega_y \sin\gamma)^2 - (-\omega_x \sin\gamma + \omega_y \cos\gamma)^2] \quad \text{(D-460)}$$

$$A_{61} = I_{\zeta\zeta_1} \quad \text{(D-461)}$$

Simplification of Force and Moment Equations and Determination of Rotor Pivot Forces with Mesh No. 1 in Round-On-Round Contact

X-Component of the Force Equation

Equation D-433 is now rewritten in the following manner

$$-F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L} = A_{62} + A_{63}\dot{\phi}_1 + A_{64}\dot{\phi}_1^2 + A_{65}\ddot{\phi}_1$$

$$+ A_{66R}F_{12} \quad \text{(D-462)}$$

where

$$A_{62} = m_1 r_{c1}[-\omega_y^2 \cos\gamma + \omega_x \omega_y \sin\gamma - \omega_z^2 \cos\gamma - \dot{\omega}_z \sin\gamma] + m_1 O_x \quad \text{(D-463)}$$

$$A_{63} = -2m_1 r_{c1}\omega_z \cos\gamma \quad \text{(D-464)}$$

$$A_{64} = -m_1 r_{c1}\cos\gamma \quad \text{(D-465)}$$

$$A_{65} = -m_1 r_{c1}\sin\gamma \quad \text{(D-466)}$$

$$A_{66R} = \cos\lambda_1 - \mu s_{1R}\sin\lambda_1 \quad \text{(D-467)}$$

Y-Component of the Force Equation

Equation D-434 becomes

$$-F_{y1u} - \mu F_{x1u} + F_{y1L} + \mu F_{x1L} = A_{67} + A_{68}\dot{\phi}_1 + A_{69}\dot{\phi}_1^2 + A_{70}\ddot{\phi}_1$$

$$+ A_{71R}F_{12} \qquad \text{(D-468)}$$

where

$$A_{67} = m_1 r_{c1}[-\omega_x^2 \sin\gamma + \omega_x\omega_y \cos\gamma - \omega_z^2 \sin\gamma - \dot{\omega}_z \cos\gamma] + m_1 O_y \qquad \text{(D-469)}$$

$$A_{68} = -2m_1 r_{c1}\omega_z \sin\gamma \qquad \text{(D-470)}$$

$$A_{69} = -m_1 r_{c1} \sin\gamma \qquad \text{(D-471)}$$

$$A_{70} = m_1 r_{c1} \cos\gamma \qquad \text{(D-472)}$$

$$A_{71R} = (\sin\lambda_1 + \mu s_{1R} \cos\lambda_1) \qquad \text{(D-473)}$$

Z-Component of the Force Equation

Equation D-435 is rewritten in its tilded form directly

$$\tilde{F}_{z1} = A_{72} + A_{73}\dot{\phi}_1 \qquad \text{(D-474)}$$

where

$$A_{72} = |m_1 r_{c1}[\omega_z(\omega_x \cos\gamma + \omega_y \sin\gamma) + \dot{\omega}_x \sin\gamma - \dot{\omega}_y \cos\gamma] + m_1 O_z| \qquad \text{(D-475)}$$

$$A_{73} = |2m_1 r_{c1}[\omega_x \cos\gamma + \omega_y \sin\gamma]| \qquad \text{(D-476)}$$

The components of the rotor moment equations are now written according to equation D-436.

X-Component of Moment Equation

With the help of equations D-440, D-441, and D-449, the following is obtained

$$\mu L_u F_{x1u} + L_u F_{y1u} + \mu L_L F_{x1L} + L_L F_{y1L} = m_1 r_{c1} O_z \sin\gamma + A_{52} + A_{53}\dot{\phi}_1$$

$$+ A_{54}\dot{\phi}_1^2 + A_{55}\ddot{\phi}_1 \qquad \text{(D-477)}$$

Y-Component of Moment Equation

Again with the help of equations D-440, D-441, i.e., its y-factors, as well as equation D-454, the following is found

$$-L_u F_{x1u} + \mu L_u F_{y1u} + \mu L_L F_{y1L} - L_L F_{x1L} = m_1 r_{c1} O_z \cos\gamma + A_{56} + A_{57}\dot{\phi}_1$$

$$+ A_{58}\dot{\phi}_1^2 + A_{59}\ddot{\phi}_1 \qquad \text{(D-478)}$$

Z-Component of Moment Equation

Again, using the Z-components of equations D-440 and D-441, together with equation D-459, obtained for the Z-component of the moment expression

$$a_{G1} F_{12}\left[\sin\left(\phi_1 - \delta_{G1} - \lambda_1\right) - \mu s_{1R} \cos\left(\phi_1 - \delta_{G1} - \lambda_1\right)\right] - \mu s_{1R} \rho_{G1} F_{12}$$

$$-\mu \rho_{f1} \tilde{F}_{z1} - \mu \rho_1 \left(F_{x1u} + F_{y1u} + F_{x1L} + F_{y1L}\right) = -m_1 r_{c1}\left[O_x \sin\gamma - O_y \cos\gamma\right]$$

$$+ A_{60} + A_{61}\ddot{\phi}_1 \qquad \text{(D-479)}$$

Solution of Rotor Pivot Forces. To obtain the rotor pivot forces, equations D-462, D-468, D-477, and D-478 must be solved simultaneously. Therefore

$$-F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L} = B_{11R} \tag{D-480}$$

$$-\mu F_{x1u} - F_{y1u} + \mu F_{x1L} + F_{y1L} = B_{12R} \tag{D-481}$$

$$\mu L_u F_{x1u} + L_u F_{y1u} + \mu L_L F_{x1L} + L_L F_{y1L} = B_{13} \tag{D-482}$$

$$-L_u F_{x1u} + \mu L_u F_{y1u} - L_L F_{x1L} + \mu L_L F_{y1L} = B_{14} \tag{D-483}$$

where

$$B_{11R} = A_{62} + A_{63}\dot{\phi}_1 + A_{64}\dot{\phi}_1^{\,2} + A_{65}\ddot{\phi}_1 + A_{66R}F_{12} \tag{D-484}$$

$$B_{12R} = A_{67} + A_{68}\dot{\phi}_1 + A_{69}\dot{\phi}_1^{\,2} + A_{70}\ddot{\phi}_1 + A_{71R}F_{12} \tag{D-485}$$

$$B_{13} = m_1 r_{c1} O_z \sin\gamma + A_{52} + A_{53}\dot{\phi}_1 + A_{54}\dot{\phi}_1^{\,2} + A_{55}\ddot{\phi}_1 \tag{D-486}$$

$$B_{14} = -m_1 r_{c1} O_z \cos\gamma + A_{56} + A_{57}\dot{\phi}_1 + A_{58}\dot{\phi}_1^{\,2} + A_{59}\ddot{\phi}_1 \tag{D-487}$$

Since equations D-480 to D-483 together have the same general form as equation D-67 for the pallet, the forms of the pallet pivot force solutions for the rotor pivot forces may be used. It must be kept in mind that for the rotor the factor μ must be substituted for A_{11}. Then, according to equation D-73

$$D_1 = [\,(L_u + L_L)\,(1 + \mu^2)\,]^2 \tag{D-488}$$

Parallel to equation D-80, the determinant $D_{F_{x1u}}$ becomes

$$D_{F_{x1u}} = (L_u + L_L)(1 + \mu^2)[-L_L B_{11R} - \mu L_L B_{12R} + \mu B_{13} - B_{14}] \qquad \text{(D-489)}$$

After appropriate substitution of equations D-484 to D-487, parallel to equations D-81 to D-87, the following is obtained for the conservative rotor pivot force

$$\tilde{F}_{x1u} = \frac{\tilde{D}_{F_{x1u}}}{D_1} = \frac{1}{L_T\ (1+\mu^2)}\ [C_{37} + C_{38}\dot{\phi}_1 + C_{39}\dot{\phi}_1^2 + C_{40}\ddot{\phi}_1 + C_{41R}F_{12}] \qquad \text{(D-490)}$$

where

$$C_{37} = |-L_L A_{62} + \mu\ (A_{52} - L_L A_{67}) - A_{56} + m_1 r_{c1} O_z\ (\mu \sin\gamma + \cos\gamma)\ | \qquad \text{(D-491)}$$

$$C_{38} = |-L_L A_{63} + \mu(A_{53} - L_L A_{68}) - A_{57}| \qquad \text{(D-492)}$$

$$C_{39} = |-L_L A_{64} + \mu(A_{54} - L_L A_{69}) - A_{58}| \qquad \text{(D-493)}$$

$$C_{40} = |-L_L A_{65} + \mu(A_{55} - L_L A_{70}) - A_{59}| \qquad \text{(D-494)}$$

$$C_{41R} = |-L_L(A_{66R} + \mu A_{71R})| \qquad \text{(D-495)}$$

Parallel to equation D-89, the determinant $D_{F_{y1u}}$ becomes

$$D_{F_{y1u}} = (L_u + L_L)(1 + \mu^2)\{\mu L_L B_{11R} - L_L B_{12R} + B_{13} + \mu B_{14}\} \qquad \text{(D-496)}$$

After appropriate substitution of equations D-484 to D-487, parallel to equations D-91 to D-96, it is found that

$$\tilde{F}_{y1u} = \frac{\tilde{D}_{F_{y1u}}}{D_1} = \frac{1}{L_T\ (1+\mu^2)}\ [C_{42} + C_{43}\dot{\phi}_1 + C_{44}\dot{\phi}_1^2 + C_{45}\ddot{\phi}_1 + C_{46R}F_{12}] \qquad \text{(D-497)}$$

where

$$C_{42} = |-L_L A_{67} + \mu\,(A_{56} + L_L A_{62}) + A_{52} + m_1 r_{c1} O_z\,(\sin\gamma - \mu\cos\gamma)| \qquad \text{(D-498)}$$

$$C_{43} = |-L_L A_{68} + \mu(L_L A_{63} + A_{57}) + A_{53}| \qquad \text{(D-499)}$$

$$C_{44} = |-L_L A_{69} + \mu(L_L A_{64} + A_{58}) + A_{54}| \qquad \text{(D-500)}$$

$$C_{45} = |-L_L A_{70} + \mu(L_L A_{65} + A_{59}) + A_{55}| \qquad \text{(D-501)}$$

$$C_{46R} = |L_L(\mu A_{66R} - A_{71R})| \qquad \text{(D-502)}$$

Parallel to equation D-99, the determinant $D_{F_{x1L}}$ becomes

$$D_{F_{x1L}} = (L_u + L_L)\left(1 + \mu^2\right)\left\{L_u B_{11R} + \mu L_u B_{12R} + \mu B_{13} - B_{14}\right\} \qquad \text{(D-503)}$$

Again, equations D-484 to D-487 are substituted into the above. Then proceed parallel to equations D-101 to D-106. Finally

$$\tilde{F}_{x1L} = \frac{\tilde{D}_{F_{x1L}}}{D_1} = \frac{1}{L_T\,(1 + \mu^2)}\,[C_{47} + C_{48}\dot{\phi}_1 + C_{49}\dot{\phi}_1^2 + C_{50}\ddot{\phi}_1 + C_{51R} F_{12}] \qquad \text{(D-504)}$$

where

$$C_{47} = |L_u A_{62} + \mu(L_u A_{67} + A_{52}) - A_{56} + m_1 r_{c1} O_z\,(\mu\sin\gamma + \cos\gamma)| \qquad \text{(D-505)}$$

$$C_{48} = |L_u A_{63} + \mu(L_u A_{68} + A_{53}) - A_{57}| \qquad \text{(D-506)}$$

$$C_{49} = |L_u S_{64} + \mu(L_u A_{69} + A_{54}) - A_{58}| \qquad \text{(D-507)}$$

$$C_{50} = |L_u A_{65} + \mu(L_u A_{70} + A_{55}) - A_{59}| \qquad \text{(D-508)}$$

$$C_{51R} = |L_u(A_{66R} + \mu A_{71R})| \qquad \text{(D-509)}$$

Parallel to equation D-109, the determinant $D_{F_{y1L}}$ becomes

$$D_{F_{y1L}} = (L_u + L_L)(1 + \mu^2)\{-\mu L_u B_{11R} + L_u B_{12R} + B_{13} + \mu B_{14}\} \tag{D-510}$$

After substitution of equations D-484 to D-487, proceed parallel to equation D-111

$$\tilde{F}_{y1L} = \frac{\tilde{D}_{F_{y1L}}}{D_1} = \frac{1}{L_T\ (1 + \mu^2)}\ [C_{52} + C_{53}\dot{\phi}_1 + C_{54}\dot{\phi}_1^2 + C_{55}\ddot{\phi}_1 + C_{56R}F_{12}] \tag{D-511}$$

where

$$C_{52} = |L_u A_{67} + \mu(A_{56} - L_u A_{62}) + A_{52} + m_1 r_{c1} O_z\ (\sin\gamma - \mu\cos\gamma)| \tag{D-512}$$

$$C_{53} = |L_u A_{68} + \mu(A_{57} - L_u A_{63}) + A_{53}| \tag{D-513}$$

$$C_{54} = |L_u A_{69} + \mu(A_{58} - L_u A_{64}) + A_{54}| \tag{D-514}$$

$$C_{55} = |L_u A_{70} + \mu(A_{59} - L_u A_{65}) + A_{55}| \tag{D-515}$$

$$C_{56R} = |L_u(A_{71R} - \mu A_{66R})\ | \tag{D-516}$$

Substitution of Tilded Pivot Forces Into Z-Component of Moment Equation. The sum of the pivot forces in equations D-479 is replaced by the sum of the tilded pivot forces, as given by equations D-490, D-497, D-504, and D-511. Then

$$F_{x1u} + F_{y1u} + F_{x1L} + F_{y1L} \approx \tilde{F}_{x1u} + \tilde{F}_{y1u} + \tilde{F}_{x1L} + \tilde{F}_{y1L} = A_{74}$$

$$+ A_{75}\dot{\phi}_1 + A_{76}\dot{\phi}_1^{\,2} + A_{77}\ddot{\phi}_1 + A_{78R}F_{12} \tag{D-517}$$

where

$$A_{74} = \frac{C_{37} + C_{42} + C_{47} + C_{52}}{L_T\left(1 + \mu^2\right)} \tag{D-518}$$

$$A_{75} = \frac{C_{38} + C_{43} + C_{48} + C_{53}}{L_T\left(1 + \mu^2\right)} \tag{D-519}$$

$$A_{76} = \frac{C_{39} + C_{44} + C_{49} + C_{54}}{L_T\left(1 + \mu^2\right)} \tag{D-520}$$

$$A_{77} = \frac{C_{40} + C_{45} + C_{50} + C_{55}}{L_T\left(1 + \mu^2\right)} \tag{D-521}$$

$$A_{78R} = \frac{C_{41R} + C_{46R} + C_{51R} + C_{56R}}{L_T\left(1 + \mu^2\right)} \tag{D-522}$$

The above is now substituted, together with the thrust friction according to equation D-474, into the moment expression D-479, and all friction moments must be examined for proper sign to oppose motion.

$$a_{G1}F_{12}\left[\sin\left(\phi_1 - \delta_{G1} - \lambda_1\right) - \mu s_{1R}\cos\left(\phi_1 - \delta_{G1} - \lambda_1\right)\right] - \mu s_{1R}\rho_{G1}F_{12}$$

$$- \mu\rho_{f1}\left[A_{72} \pm A_{73}\dot{\phi}_1\right] - \mu\rho_1\left[A_{74} \pm A_{75}\dot{\phi}_1 \pm A_{76}\dot{\phi}_1^2 \pm A_{77}\ddot{\phi}_1 + A_{78R}F_{12}\right]$$

$$= -m_1 r_{c1}\left[O_x\sin\gamma - O_y\cos\gamma\right] + A_{60} + A_{61}\ddot{\phi}_1 \tag{D-523}$$

Equation D-523 is rearranged to

$$F_{12}\left[a_{G1}\left(\sin\left(\phi_1 - \delta_{G1} - \lambda_1\right) - \mu s_{1R}\cos\left(\phi_1 - \delta_{G1} - \lambda_1\right)\right) - \mu s_{1R}\rho_{G1} - \mu\rho_1 A_{78R}\right]$$

$$\pm\,\mu\left[\rho_{f1}A_{72} + \rho_1 A_{74}\right] \pm \mu\left[\rho_{f1}A_{73} + \rho_1 A_{75}\right]\dot{\phi}_1 \pm \mu\rho_1 A_{76}\dot{\phi}_1^2 \pm \mu\rho_1 A_{77}\ddot{\phi}_1$$

$$= A_{60} + A_{61}\ddot{\phi}_1 - m_1 r_{c1}\left[O_x\sin\gamma - O_y\cos\gamma\right] \qquad \text{(D-524)}$$

Now consider the signs of the various friction moments, recalling that a reversal in the gear train motion will cause a change in the sign of μ in the program. The following moment components must have negative signs during positive rotation

$$1:\ -\mu F_{12}\rho_1 A_{78R} \qquad \text{(D-525)}$$

since F_{12} and ρ_1 are positive, and A_{78R} is a sum of absolute values.

$$2:\ -\mu[\rho_{f1}A_{72} + \rho_1 A_{74}] \qquad \text{(D-526)}$$

since ρ_{f1} and ρ_1 are positive, while A_{72} and A_{74} are both absolute values.

$$3:\ -\mu\rho_1 A_{76}\dot{\phi}_1^2 \qquad \text{(D-527)}$$

since A_{76} is also a sum of absolute values.

The sign of the term containing $\dot{\phi}_1$ must be decided by the sign of this angular velocity only. Therefore, the coefficient of friction must not change sign on motion reversal, and the expression takes the form

$$-|\mu|\,[\rho_{f1}A_{73} + \rho_1 A_{75}]\dot{\phi}_1 \qquad \text{(D-528)}$$

The choice of signs in the coefficient of the angular acceleration $\ddot{\phi}_1$ is discussed in detaile in appendix F of reference 4. This leads to the computational rules of equations D-535 and D-536 below.

With the above considerations, equation D-524 becomes

$$A_{79R}F_{12} - A_{80} - A_{81}\dot{\phi}_1 \; A_{82}\dot{\phi}_1^{\,2} = I_{1R}\ddot{\phi}_1 + A_{70} - m_1 r_{c1}[O_x \sin\gamma - O_y \cos\gamma] \qquad \text{(D-529)}$$

where

$$A_{79R} = a_{G1}\left[\sin\left(\phi_1 - \delta_{G1} - \lambda_1\right) - \mu s_{1R}\cos\left(\phi_1 - \delta_{G1} - \lambda_1\right)\right] - \mu$$

$$[\,s_{1R}\rho_{G1} + \rho_1 A_{78R}] \qquad \text{(D-530)}$$

$$A_{80} = \mu[\rho_{f1}A_{72} + \rho_1 A_{74}] \qquad \text{(D-531)}$$

$$A_{81} = |\mu|\,[\rho_{f1}A_{73} + \rho_1 A_{75}] \qquad \text{(D-532)}$$

$$A_{82} = \mu\rho_1 A_{76} \qquad \text{(D-533)}$$

$$A_{83} = |\mu|\,\rho_1 A_{77} \qquad \text{(D-534)}$$

Further

$$I_{1R} = A_{61} + A_{83} \qquad \text{(D-535)}$$

when $\dot{\phi}_1$ and $\ddot{\phi}_1$ have the same signs, and

$$I_{1R} = A_{61} - A_{83} \qquad \text{(D-536)}$$

when $\dot{\phi}_1$ and $\ddot{\phi}_1$ have opposite signs.

General Form of Contact Force F_{12} in Terms of Rotor Parameters When Mesh No. 1 is in Round-on-Round Contact. Adjustment for Contact Mode of Mesh No. 2.

Equation D-529 may now be rewritten to obtain a general expression for the contact force F_{12} when mesh no. 1 is in round-on-round contact

$$F_{12} = \frac{I_{1R}\ddot{\phi}_1 + A_{81}\dot{\phi}_1 + A_{82}\dot{\phi}_1^2 + A_{80} + A_{60} - m_1 r_{c1}[O_x \sin\gamma - O_y \cos\gamma]}{A_{79R}} \quad \text{(D-537)}$$

When mesh no. 2 is at the same time in the round-on-round mode, the angular velocity $\dot{\phi}_1$ must be obtained from equation F-142 of appendix F, while the angular acceleration $\ddot{\phi}_1$ is given by equation F-143.

For mesh 2 simultaneously in the round-on-flat contact $\dot{\phi}_1$ and $\ddot{\phi}_1$ are given by equations F-154 and F-155, respectively.

Mesh No. 1 in Round-on-Flat Contact

Force Equations for the Rotor and Gear No. 1 With Mesh No. 1 in Round-on-Flat Contact.

A top view of the rotor and gear no. 1 in the round-on-flat contact mode is shown in figure D-12a. The contact force on the gear is now $\overline{F}_{21F}$ and the associated friction force is given by $\overline{F}_{f21F}$. Thus, (again, see ref 5) with both forces equal and opposite to F_{12F} and F_{f12F}, of equations D-696 and D-697, respectively

$$\overline{F}_{21F} = F_{12F}\overline{n}_{NF1} \ , \quad \text{(D-538)}$$

where, according to equation G-23 of reference 5

$$\overline{n}_{NF1} = -\sin(\phi_{2P} + \alpha_{P1})\overline{i} + \cos(\phi_{2P} + \alpha_{P1})\overline{j} \quad \text{(D-539)}$$

Further

$$\overline{F}_{f21F} = -\mu s_{1F} F_{12F}\overline{n}_{F1} \ , \quad \text{(D-540)}$$

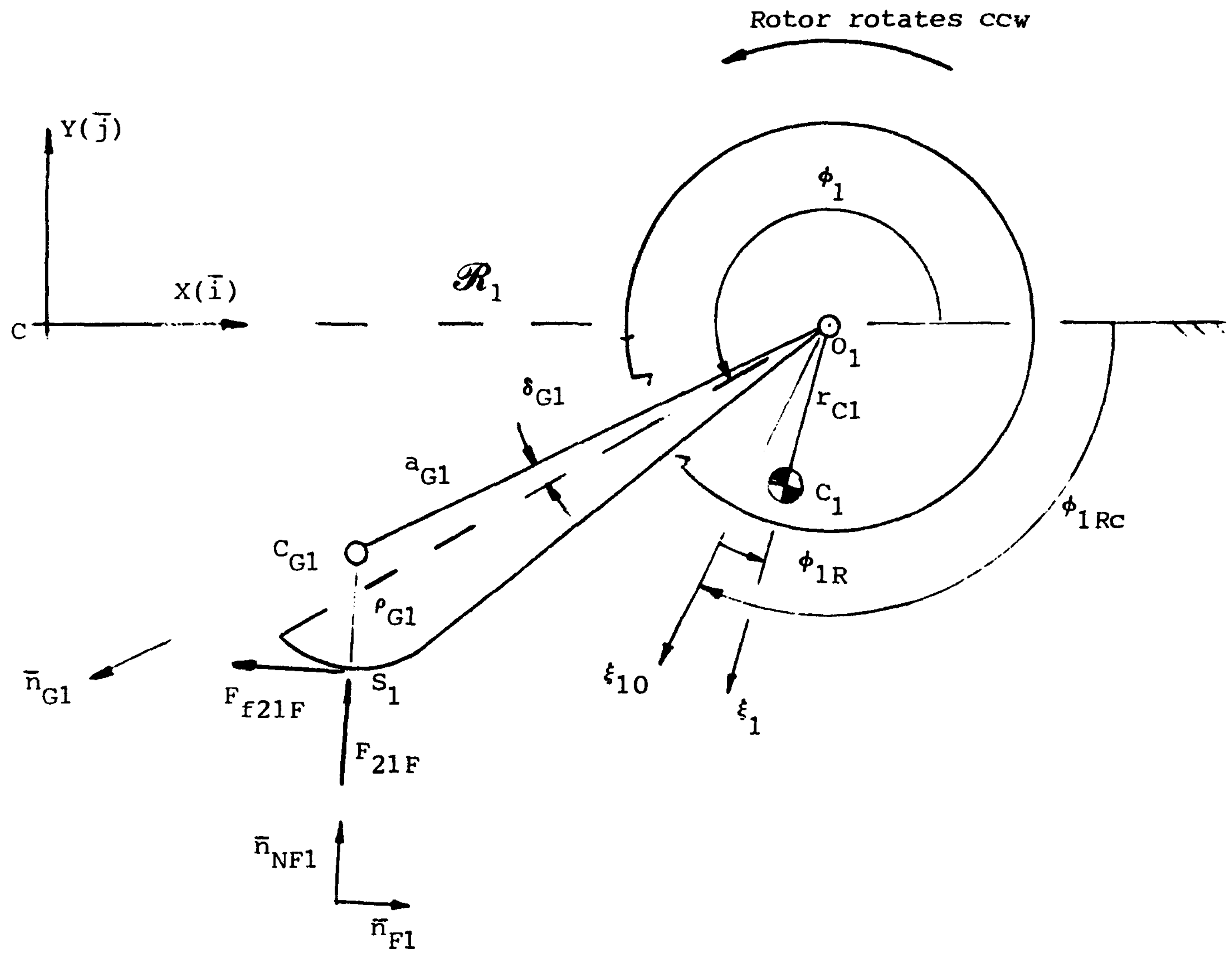


Figure D-12a. Top view of free body diagram of rotor and gear no. 1. Mesh no. 1 is in round-on-flat contact.

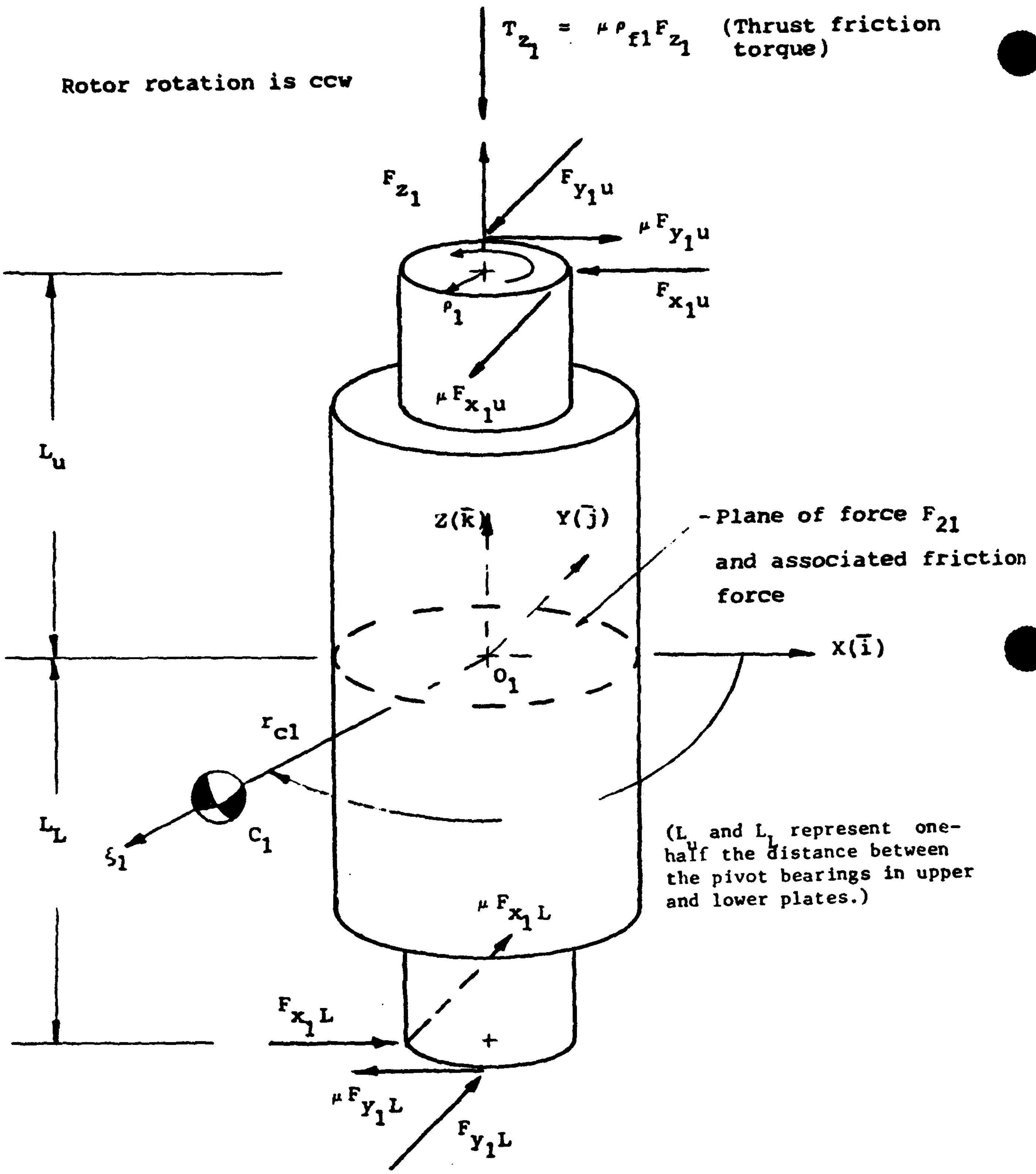


Figure D-12b. Rotor and gear no. 1. Normal forces, friction forces, and thrust friction torque acting on rotor pivots. (Same as figure D-11b. Not influenced by type of mesh contact.)

where, according to equation G-22 of reference 5

$$\bar{n}_{F1} = -\cos(\phi_{2P} + \alpha_{P1})\bar{i} + \sin(\phi_{2P} + \alpha_{P1})\bar{j} \tag{D-541}$$

The signum function s_{1F} becomes with the help of equation G-33 of reference 5, or equation F-24 of appendix F

$$S_{1F} = \frac{V_{S_1/T_{1_F}}}{\left|V_{S_1/T_{1_F}}\right|} \tag{D-542}$$

A free body diagram of the rotor pivot, with all normal and frictional forces, is given by figure D-12b. Since the rotation direction of the rotor does not depend on the mesh contact type, this figure is the same as figure D-11b.

The force equation of the rotor is formulated according to equation D-431

$$F_{12F}\bar{n}_{NF1} - \mu s_{1F}F_{12F}\bar{n}_{F1} + F_{z1}\bar{k} - F_{x1u}\bar{i} - F_{y1u}\bar{j} - \mu F_{x1u}\bar{j} + \mu F_{y1u}\bar{i}$$

$$+ F_{x1L}\bar{i} + F_{y1L}\bar{j} + \mu F_{x1L}\bar{j} - \mu F_{y1L}\bar{i} = m_1\bar{A}_{C_1/ground} \tag{D-543}$$

The unit vectors of equations D-539 and D-541 are now substituted into equation D-543. Subsequently, the force component expressions may be written with the help of equation D-425

X-Component of Rotor Force Equation

$$-F_{12F}\sin(\phi_{2P} + \alpha_{P1}) - \mu s_{1F}F_{12F}\cos(\phi_{2P} + \alpha_{P1}) - F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L}$$

$$= m_1\left[-r_{c1}\left\{\omega_y^2\cos\gamma - \omega_x\omega_y\sin\gamma + \left(\omega_z + \dot{\phi}_1\right)^2\cos\gamma + \left(\dot{\omega}_z + \ddot{\phi}_1\right)\sin\gamma\right\} + O_x\right] \tag{D-544}$$

Y-Component of Rotor Force Equation

$$-F_{12F}\cos(\phi_{2P} + \alpha_{P1}) - \mu s_{1F}F_{12F}\sin(\phi_{2P} + \alpha_{P1}) - F_{y1u} - \mu F_{x1u} + F_{y1L} + \mu F_{x1L}$$

$$= m_1\left[-r_{c1}\left\{\omega_y^2\sin\gamma - \omega_x\omega_y\cos\gamma + \left(\omega_z + \dot{\phi}_1\right)^2\sin\gamma - \left(\dot{\omega}_z + \ddot{\phi}_1\right)\cos_\gamma\right\} + O_y\right] \tag{D-545}$$

Z-Component of Rotor Force Equation

$$F_{z1} = m_1\{r_{c1}[(\omega_x\cos\gamma + \omega_y\sin\gamma)(\omega_z + 2\dot{\phi}_1) + \dot{\omega}_x\sin\gamma - \dot{\omega}_y\cos\gamma] + O_z\} \quad \text{(D-546)}$$

Moment Equations for the Rotor and Gear No. 1 With Mesh No. 1 in Round-on-Flat Contact

The form of the moment equation for the round-on-flat case of the rotor is identical to equation D-436.

Determination of M_{O1}. The moment $\overline{M}_{21F}$ of the contact force $\bar{F}_{t21F}$ with respect to pivot O_1 is given by

$$\overline{M}_{21F} = (a_{G1}\bar{n}_{G1} - \rho_{G1}\bar{n}_{NF1}) \times (F_{12F}\bar{n}_{NF1} - \mu s_{1F}F_{12F}\bar{n}_{F1}) \quad \text{(D-547)}$$

This becomes with the help of equations D-549, D-541, and D-438

$$\overline{M}_{21F} = a_{G1}F_{12F}[\cos(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}) + \mu s_{1F}\sin$$

$$(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1})]\bar{k} - \mu s_{1F}\rho_{G1}F_{12F}\bar{k} \quad \text{(D-548)}$$

Similar to equation D-440, the moments due to the various pivot forces may also for this contact case be adapted from equation D-32. Again, because of the CCW rotation of the rotor, $s_5 = +1$. Further, μ_1 becomes μ and the subscripts are changed from the primed to the unprimed coordinate system. With equation D-548, the complete expression for $\overline{M}_{O1}$ becomes

$$\overline{M}_{O1} = [L_uF_{y1u} + \mu L_uF_{x1u} + L_LF_{y1L} + \mu L_LF_{x1L}]\bar{i} + [\mu L_uF_{y1u} - \mu L_uF_{x1u}$$

$$+ \mu L_LF_{y1L} - L_LF_{x1L}]\bar{j} + \{a_{G1}F_{12F}[\cos(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}) + \mu s_{1F}\sin$$

$$(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1})] - \mu s_{1F}\rho_{G1}F_{12F} - \mu\rho_{f1}\tilde{F}_{z1} - \rho_1\mu F_{y1u} - \rho_1\mu F_{x1u}$$

$$- \rho_1\mu F_{y1L} - \rho_1\mu F_{x1L}\}\bar{k} \quad \text{(D-549)}$$

Note the use of the tilded form of $\tilde{F}_{z1}$ in the above. This has been defined by equation D-474.

First Term on Right Hand Side of Equation D-436. As in equation D-441, the first term on the right hand side of equation D-436 remains

$$m_1 r_{c1}[O_z \sin\gamma \bar{i} - O_z \cos\gamma \bar{j} - (O_x \sin\gamma - O_y \cos\gamma)\bar{k}] \tag{D-550}$$

Time Rate of Change of Angular Momentum $\bar{H}_{O1}$ of Rotor With Respect to Its Pivot O_1. The applicable component expressions for the second term on the right hand side of equation D-436 remain the same as given earlier for the round-on-round contact mode.

Thus, according to equation D-449

$$\dot{H}_{O1x} = A_{52} + A_{53}\dot{\phi}_1 + A_{54}\dot{\phi}_1^{\,2} + A_{55}\ddot{\phi}_1 \tag{D-551}$$

Further, from equation D-454

$$\dot{H}_{O1y} = A_{56} + A_{57}\dot{\phi}_1 + A_{58}\dot{\phi}_1^{\,2} + A_{59}\ddot{\phi}_1 \,, \tag{D-552}$$

and according to equation D-459

$$\dot{H}_{O1z} = A_{60} + A_{61}\ddot{\phi}_1 \tag{D-553}$$

Simplification of Force and Moment Equations and Determination of Rotor Pivot Forces with Mesh No. 1 in Round-on-Flat Contact

X-Component of the Force Equation

Equation D-544 is now rewritten in the following manner

$$- F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L}$$
$$= A_{62} + A_{63}\dot{\phi}_1 + A_{64}\dot{\phi}_1^2 + A_{65}\ddot{\phi}_1 + A_{66F}F_{12F} \tag{D-554}$$

where, A_{62}, A_{63}, A_{64}, and A_{65} remain as given by equations D-463 to D-466, respectively, and now

$$A_{66F} = \sin(\phi_{2P} + \alpha_{P1}) + \mu s_{1F} \cos(\phi_{2P} + \alpha_{P1}) \qquad \text{(D-555)}$$

Y-Component of the Force Equation

Equation D-545 becomes

$$- F_{y1u} - \mu F_{x1u} + F_{y1L} + \mu F_{x1L}$$

$$= A_{67} + A_{68}\,\dot{\phi}_1 + A_{69}\,\dot{\phi}_1^2 + A_{70}\,\ddot{\phi}_1 + A_{71F}F_{12F} \qquad \text{(D-556)}$$

where A_{67}, A_{68}, A_{69}, and A_{70} remain as given by equations D-469 to D-472, respectively, and

$$A_{71F} = \mu s_{1F} \sin(\phi_{2P} + \alpha_{P1}) - \cos(\phi_{2P} + \alpha_{P1}) \qquad \text{(D-557)}$$

Z-Component of Force Equation

Equation D-546 is again rewritten in the tilded form, and is identical with equation D-474, i.e.,

$$\tilde{F}_{Z1} = A_{72} + A_{73}\,\dot{\phi}_1 \qquad \text{(D-558)}$$

where A_{72} and A_{73} are given by equations D-475 and D-476, respectively.

The components of the rotor moment equation are again written according to equation D-436.

X-Component of Moment Equation

With the help of equations D-549, D-550, and D-551 the following is obtained

$$\mu L_u F_{x1u} + L_u F_{y1u} + \mu L_L F_{x1L} + L_L F_{y1L}$$

$$= m_1 r_{c1} O_z \sin\gamma + A_{52} + A_{53}\,\dot{\phi}_1 + A_{54}\,\dot{\phi}_1^2 + A_{55}\,\ddot{\phi}_1 \qquad \text{(D-559)}$$

Y-Component of Moment Equation

Again with the help of equations D-549 and D-550, i.e., its y-factors, as well as equation D-552 the following is found

$$-L_u F_{x1u} + \mu L_u F_{y1u} + \mu L_L F_{y1L} - L_L F_{x1L}$$

$$= -m_1 r_{c1} O_z \cos\gamma + A_{56} + A_{57}\dot{\phi}_1 + A_{58}\dot{\phi}_1^2 + A_{59}\ddot{\phi}_1 \qquad \text{(D-560)}$$

Z-Component of Moment Equation

Again, using the Z-components of equations D-549 and D-550 together with equation D-553, obtained for the Z-component of the moment expression

$$a_{G1}F_{12F}[\cos(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}) + \mu s_{1F}\sin(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1})]$$

$$-\mu s_{1F}\rho_{G1}F_{12F} - \mu\rho_{f1}\widetilde{F}_{z1} - \mu\rho_1(F_{x1u} + F_{y1u} + F_{x1L} + F_{y1L})$$

$$= -m_1 r_{c1}[O_x \sin\gamma - O_y \cos\gamma] + A_{60} + A_{61}\ddot{\phi}_1 \qquad \text{(D-561)}$$

Solution of Rotor Pivot Forces

To obtain the rotor pivot forces, equations D-554, D-556, D-559, and D-560 must be solved simultaneously. Therefore

$$-F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L} = B_{11F} \qquad \text{(D-562)}$$

$$-\mu F_{x1u} - F_{y1u} + \mu F_{x1L} + F_{y1L} = B_{12F} \qquad \text{(D-563)}$$

$$\mu L_u F_{x1u} + L_u F_{y1u} + \mu L_L F_{x1L} + L_L F_{y1L} = B_{13} \qquad \text{(D-564)}$$

$$-L_u F_{x1u} + \mu L_u F_{y1u} - L_L F_{x1L} + \mu L_L F_{y1L} = B_{14} \qquad \text{(D-565)}$$

where

$$B_{11F} = A_{62} + A_{63}\,\dot{\phi}_1 + A_{64}\,\dot{\phi}_1^2 + A_{65}\,\ddot{\phi}_1 + A_{66F}F_{12F} \qquad \text{(D-566)}$$

$$B_{12F} = A_{67} + A_{68}\,\dot{\phi}_1 + A_{69}\,\dot{\phi}_1^2 + A_{70}\,\ddot{\phi}_1 + A_{71F}F_{12F} \qquad \text{(D-567)}$$

B_{13} = same as equation D-486

B_{14} = same as equation D-487

Similar to the round-on-round case of the rotor (see equations D-480 to D-483 and subsequent discussion) equations D-562 to D-565 together have the same general form as equation D-67 for the pallet. Thus, the pallet pivot force solutions may again be adapted to the present round-on-flat contact case of the rotor. As earlier, the coefficient of friction μ must replace the parameter A_{11}. Then, according to equation D-73

$$D_1 = \left[(L_u + L_L)\left(1 + \mu^2\right)\right]^2 \qquad \text{(D-568)}$$

Parallel to equation D-80, the determinant $D_{F_{x1u}}$ becomes

$$D_{F_{x1u}} = (L_u + L_L)\left(1 + \mu^2\right)\left[-L_L B_{11F} - \mu L_L B_{12F} + \mu B_{13} - B_{14}\right] \qquad \text{(D-569)}$$

After appropriate substitution of equations D-566, D-567 as well as D-486 and D-487, parallel to equations D-81 to D-87, the following is obtained for the conservation (tilded) rotor pivot force $\tilde{F}_{x1u}$

$$\tilde{F}_{x1u} = \frac{\tilde{D}_{F_{x1u}}}{D_1} = \frac{1}{L_T\left(1 + \mu^2\right)}\left[C_{37} + C_{38}\dot{\phi}_1 + C_{39}\dot{\phi}_1^2 + C_{40}\ddot{\phi}_1 + C_{41F}F_{12F}\right] \qquad \text{(D-570)}$$

where

C_{37} = same as equation D 491

C_{38} = same as equation D-492

C_{39} = same as equation D-493

C_{40} = same as equation D-494

and

$$C_{41F} = \left| -L_L (A_{66F} + \mu A_{71F}) \right| \tag{D-571}$$

Parallel to equation D-89, the determinant $D_{F_{y1U}}$ becomes

$$D_{F_{y1u}} = (L_u + L_L)(1 + \mu^2)\{\mu L_L B_{11F} - L_L B_{12F} + B_{13} + \mu B_{14}\} \tag{D-572}$$

After appropriate substitution of equations D-566, D-567, D-486, and D-487, parallel to equations D-91 to D-96, it is found that

$$\tilde{F}_{y1u} = \frac{\tilde{D}_{F_{y1u}}}{D_1} = \frac{1}{L_T(1 + \mu^2)}\left[C_{42} + C_{43}\dot{\phi}_1 + C_{44}\dot{\phi}_1^2 + C_{45}\ddot{\phi}_1 + C_{46F}F_{12F}\right] \tag{D-573}$$

where

C_{42} = same as equation D-498

C_{43} = same as equation D-499

C_{44} = same as equation D-500

C_{45} = same as equation D-501

and

$$C_{46F} = \left| L_L (\mu A_{66F} - A_{71F}) \right| \tag{D-574}$$

Parallel to equation D-99, the determinant $D_{F_{x1L}}$ becomes

$$D_{F_{x1L}} = (L_u + L_L)(1 + \mu^2)\{L_u B_{11F} + \mu L_u B_{12F} + \mu B_{13} - B_{14}\} \tag{D-575}$$

Again, equations D-566, D-567, D-486, and D-487 are substituted into the above. Then proceed parallel to equations D-101 to D-106. Finally

$$\tilde{F}_{x1L} = \frac{\tilde{D}_{F_{x1L}}}{D_1} = \frac{1}{L_T(1 + \mu^2)}\left[C_{47} + C_{48}\dot{\phi}_1 + C_{49}\dot{\phi}_1^2 + C_{50}\ddot{\phi}_1 + C_{51F}F_{12F}\right] \tag{D-576}$$

where

C_{47} = same as equation D-505

C_{48} = same as equation D-506

C_{49} = same as equation D-507

C_{50} = same as equation D-508

$$C_{51F} = \left| L_u \left(A_{66F} + \mu A_{71F} \right) \right| \tag{D-577}$$

Parallel to equation D-109, the determinant $D_{F_{y1L}}$ becomes

$$D_{F_{y1L}} = \left(L_u + L_L \right) \left(1 + \mu^2 \right) \left\{ -\mu L_u B_{11} + L_u B_{12} + B_{13} + \mu B_{14} \right\} \tag{D-578}$$

After substitution of equations D-566, D567, D-486, and D-487 proceed parallel to equation D-111

$$\tilde{\tilde{F}}_{y1L} = \frac{\tilde{D}_{F_{y1L}}}{D_1} = \frac{1}{L_T (1 + \mu^2)} \left[C_{52} + C_{53} \dot{\phi}_1 + C_{54} \dot{\phi}_1^2 + C_{55} \ddot{\phi}_1 + C_{56F} F_{12F} \right] \tag{D-579}$$

where

C_{52} = same as equation D-512

C_{53} = same as equation D-513

C_{54} = same as equation D-514

C_{55} = same as equation D-515

and

$$C_{56F} = \left| L_u \left(A_{71F} - \mu A_{66F} \right) \right| \tag{D-580}$$

Substitution of Tilded Pivot Forces Into Z-Component of Moment Equation. The sum of the pivot forces in equation D-561 is replaced by the sum of the tilded pivot forces, as given by equations D-570, D-573, D-576, and D-579. Then

$$F_{x1u} + F_{y1u} + F_{x1L} \approx \widetilde{F}_{x1u} + \widetilde{F}_{y1u} + \widetilde{F}_{x1L} + \widetilde{F}_{y1L}$$

$$= A_{74} + A_{75}\,\dot{\phi}_1 + A_{76}\,\dot{\phi}_1^2 + A_{77}\,\ddot{\phi}_1 + A_{78F}F_{12F} \qquad \text{(D-581)}$$

where

A_{74} = same as equation D-518

A_{75} = same as equation D-519

A_{76} = same as equation D-520

A_{77} = same as equation D-521

and

$$A_{78F} = \frac{C_{41F} + C_{46F} + C_{51F} + C_{56F}}{L_T(1 + \mu^2)} \qquad \text{(D-582)}$$

The above is now substituted, together with the thrust friction according to equation D-558, into the moment expression D-561. Again all friction moments must be examined for their sign.

$$a_{G1}F_{12F}[\cos(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}) + \mu s_{1F}\sin(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1})]$$

$$-\mu s_{1F}\rho_{G1}F_{12F} - \mu\rho_{f1}[A_{72} \pm A_{73}\,\dot{\phi}_1]$$

$$-\mu\rho_1[A_{74} \pm A_{75}\,\dot{\phi}_1 \pm A_{76}\,\dot{\phi}_1^2 \pm A_{77}\,\ddot{\phi}_1 + A_{78F}F_{12F}]$$

$$= -m_1 r_{c1}\,[O_x \sin\ \gamma - O_y \cos\gamma] + A_{60} + A_{61}\,\ddot{\phi}_1 \qquad \text{(D-583)}$$

This is rearranged to

$$F_{12F}\Big\{a_{G1}\,[\cos(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}) + \mu s_{1F}\sin(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1})]$$

$$-\mu[s_{1F}\rho_{G1} + \rho_1 A_{78F}]\Big\} \pm \mu[\rho_{F1}A_{72} + \rho_1 A_{74}]$$

$$\pm\mu[\rho_{f1}A_{73} + \rho_1 A_{75}]\dot{\phi}_1 \pm \mu\rho_1 A_{76}\,\dot{\phi}_1^2 \pm \mu\rho_1 A_{77}\,\ddot{\phi}_1$$

$$= A_{60} + A_{61}\,\ddot{\phi}_1 - m_1 r_{c1}\,[O_x \sin\gamma - O_y \cos\gamma] \qquad \text{(D-584)}$$

Now consider the signs of the various friction moments again as for equation D-524, recalling that a reversal in the gear train motion will cause a change in the sign of μ in the program. The following moment components must have negative signs during positive rotation

$$1: -\mu F_{12F}\rho_1 A_{78F} \qquad \text{(D-585)}$$

since F_{12} and ρ_1 are positive, and A_{78F} is a sum of absolute values.

$$2: -\mu[\rho_{f1}A_{72} + \rho_1 A_{74}] \qquad \text{(D-586)}$$

since ρ_{f1} and ρ_1 are positive, while A_{72} and A_{74} are both absolute values.

$$3: -\mu\rho_1 A_{76}\,\dot{\phi}_1^2 \qquad \text{(D-587)}$$

since A_{76} is also a sum of absolute values.

The sign of the term containing $\dot{\phi}_1$ must be decided by the sign of this angular velocity only. Therefore, the coefficient of friction must not change sign on motion reversal, and the expression takes the form

$$-\,|\,\mu\,|\,[\rho_{f1}A_{73} + \rho_1 A_{75}]\,\dot{\phi}_1 \qquad \text{(D-588)}$$

The choice of signs in the coefficient of the angular acceleration $\ddot{\phi}_1$ is discussed in detail in appendix F of reference 4. This leads to the computational rules of equations D-591 and D-592 below.

With the above considerations, equation D-398 becomes

$$A_{79F}F_{12} - A_{80} - A_{81}\,\dot{\phi}_1 - A_{82}\,\dot{\phi}_1^2$$

$$= I_{1R}\,\ddot{\phi}_1 + A_{60} - m_1 r_{c1}[O_x \sin\gamma - O_y \cos\gamma] \qquad \text{(D-589)}$$

where

$$A_{79F} = a_{G1}\left[\cos\left(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}\right) + \mu s_{1F} \sin\left(\phi_1 - \delta_{G1} - \phi_{2P} - \alpha_{P1}\right)\right]$$

$$- \mu[s_{1F}\rho_{G1} + \rho_1 A_{78F}] \qquad \text{(D-590)}$$

A_{80} = same as equation D-531

A_{81} = same as equation D-532

A_{82} = same as equation D-533

A_{83} = same as equation D-534

Further, as in equations D-535 and D-536

$$I_{1R} = A_{61} + A_{83} \qquad \text{(D-591)}$$

when $\dot{\phi}_1$ and $\ddot{\phi}_1$ have the same signs, and

$$I_{1R} = A_{61} - A_{83} \qquad \text{(D-592)}$$

when $\dot{\phi}_1$ and $\ddot{\phi}_1$ have opposite signs.

General Form of Contact Force F_{12F} in Terms of Rotor Parameters When Mesh No. 1 is in Round-on-Flat Contact. Adjustment for Contact Mode of Mesh No. 2

Equation D-589 may now be rewritten to obtain a general expression for the contact force F_{12F} when mesh no. 1 is in the round-on-flat mode of contact

$$F_{12F} = \frac{I_{1R}\ddot{\phi}_1 + A_{81}\dot{\phi}_1 + A_{82}\dot{\phi}_1^2 + A_{80} + A_{60} - m_1 r_{c1}\left[O_x \sin\gamma - O_y \cos\gamma\right]}{A_{79F}} \qquad \text{(D-593)}$$

When mesh no. 2 is at the same time in the round-on-round mode, the angular velocity $\dot{\phi}_1$ must be obtained from equation F-146 of appendix F, while the angular acceleration $\ddot{\phi}_1$ is given by equation F-147.

With mesh no. 2 simultaneously in the round-on-flat contact mode $\dot{\phi}_1$ and $\ddot{\phi}_1$ are obtained from equations F-150 and F-151, respectively.

DYNAMICS OF GEAR AND PINION NO. 2

(For force analysis background see reference 1)

Before the force and moment equations for the various mesh contact combinations of gear and pinion no. 2 can be written, it is first necessary to find an expression for the absolute acceleration of the gear and pinion pivot point O_2, which coincides with the center of mass C_2 of this component. A view of this compound gear in the mechanism plane and in configuration no. 2 is shown in figure D-13.

Absolute Acceleration of Gear and Pinion Pivot O_2

The absolute acceleration of pivot point O_2 is given by

$$\bar{A}_{O_2/ground} = \bar{A}_{O_2/C} + \bar{A}_{C/ground} \tag{D-594}$$

where

$\bar{A}_{C/ground}$ = Absolute acceleration of geometric center C of mechanism plane, as given by equation C-4

and

$$\bar{A}_{O_2/C} = \bar{\omega} \times (\bar{\omega} \times \Re_2 \bar{n}_2) + \dot{\bar{\omega}} \times \Re_2 n_2 \tag{D-595}$$

where

$$\bar{\omega} = \omega_x \bar{i} + \omega_y \bar{j} + \omega_z \bar{k} \tag{D-596}$$

$$\dot{\bar{\omega}} = \dot{\omega}_x \bar{i} + \dot{\omega}_y \bar{j} + \dot{\omega}_z \bar{k} \tag{D-597}$$

Further,

$$\bar{n}_2 = \cos \gamma_2 \bar{i} + \sin \gamma_2 \bar{j} \tag{D-598}$$

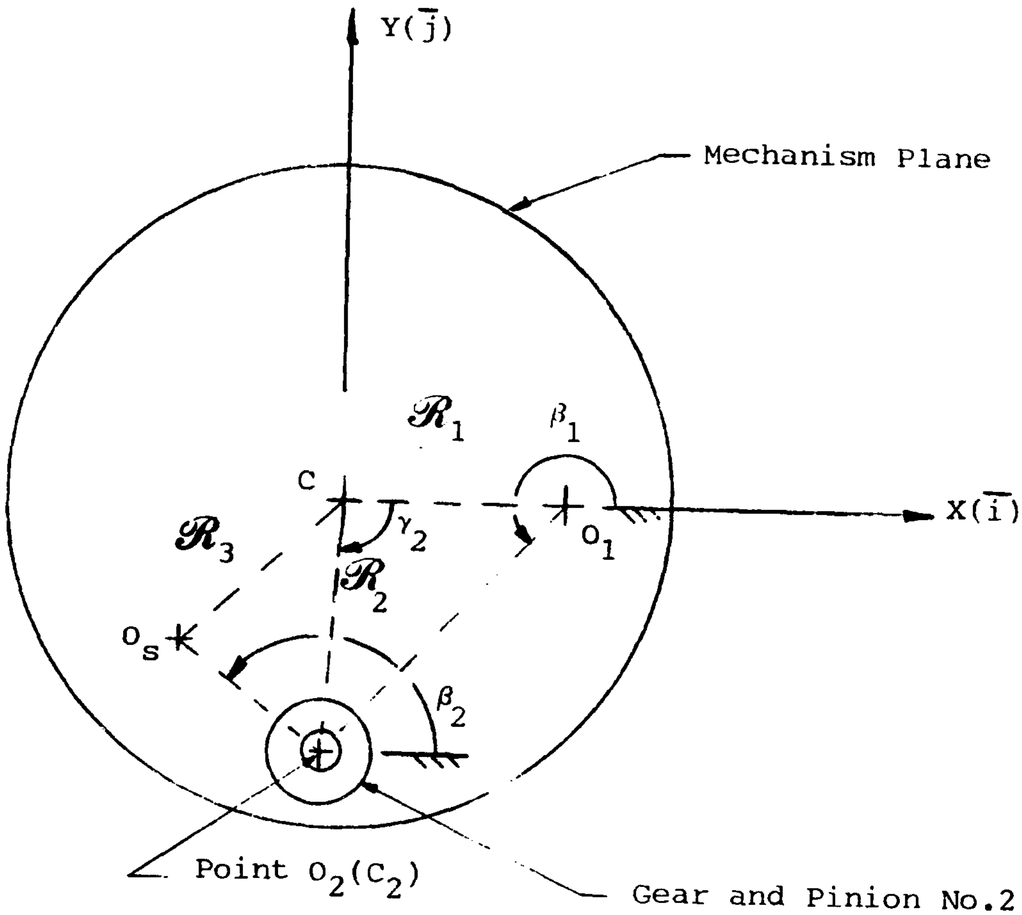


Figure D-13. Gear and pinion no. 2 in mechanism plane (shown in configuration no. 2)

and

$$\Re_{2x} = \Re_2 \cos \gamma_2 \tag{D-599}$$

$$\Re_{2y} = \Re_2 \sin \gamma_2 \tag{D-600}$$

With the above, equation D-595 becomes

$$\bar{A}_{O_2/C} = P_x\bar{i} + P_y\bar{j} + P_z\bar{k} \tag{D-601}$$

where

$$P_x = \omega_x\omega_y\Re_{2y} - \left(\omega_y^2 + \omega_z^2\right)\Re_{2x} - \dot{\omega}_z\Re_{2y} \tag{D-602}$$

$$P_y = \omega_x\omega_y\Re_{2x} - \left(\omega_x^2 + \omega_z^2\right)\Re_{2y} + \dot{\omega}_z\Re_{2x} \tag{D-603}$$

$$P_z = (\omega_x\Re_{2x} + \omega_y\Re_{2y})\,\omega_z + \dot{\omega}_x\Re_{2y} - \dot{\omega}_y\Re_{2x} \tag{D-604}$$

Finally, equation D-594 becomes

$$\bar{A}_{O_2/ground} = Q_x\bar{i} + Q_y\bar{j} + Q_z\bar{k} \tag{D-605}$$

where, with the help of equations C-4 and D-601

$$Q_x = G_x + P_x \tag{D-606}$$

$$Q_y = G_y + P_y \tag{D-607}$$

$$Q_z = G_z + P_z \tag{D-608}$$

Dynamics of Gear and Pinion No. 2 with Mesh No. 2 and Mesh No. 1 in Round-on-Round Contact

A schematic top view free body diagram of gear and pinion no. 2 with both meshes in the round-on-round contact mode is shown in figure D-14a. It shows the contact force

$$\bar{F}_{32} = -\bar{F}_{23} = -\bar{F}_{23}\bar{n}_{\lambda 2} \tag{D-609}$$

of pinion no. 3 on gear no. 2, opposite to force $\bar{F}_{23}$, as given by equation D-145a. The associated friction force $\bar{F}_{f32}$ is opposite to $\bar{F}_{f23}$, as given by equation D-146. Thus,

$$\bar{F}_{f32} = -\bar{F}_{f23} = -\omega s_{2R} F_{23} \bar{n}_{N\lambda 2} \tag{D-610}$$

The contact force $\bar{F}_{12}$ of gear no. 1 on pinion no. 2 is also shown in figure D-14a. This force is opposite in direction to contact force $\bar{F}_{21}$, which is given by equation D-426. Then

$$\bar{F}_{12} = -\bar{F}_{21} = F_{23} \bar{n}_{\lambda 1} \tag{D-611}$$

The associated friction force $\bar{F}_{f12}$ is opposite in direction to the friction force $\bar{F}_{f21}$ of equation D-428, i.e.

$$\bar{F}_{f12} = -\bar{F}_{f21}' = \mu s_{1R} F_{12} \bar{n}_{N\lambda 1} \tag{D-612}$$

A free body diagram of the pivot shaft of gear and pinion no. 2 is shown in figure D-14b. This representation of normal, friction and thrust forces and torques acting on the CW rotating component is valid regardless of the instantaneous combination of mesh contact modes.

Force Equations

The force equation is again based on Newton's law, i.e.

$$\Sigma\bar{F} = m_2 \bar{A}_{O_2/ground} \tag{D-613}$$

where

$\Sigma\bar{F}$ = sum of the pivot forces as well as the various contact forces

m_2 = mass of gear and pinion no. 2

$\bar{A}_{O_2/ground}$ = acceleration of the component center of mass, i.e., equation D-605

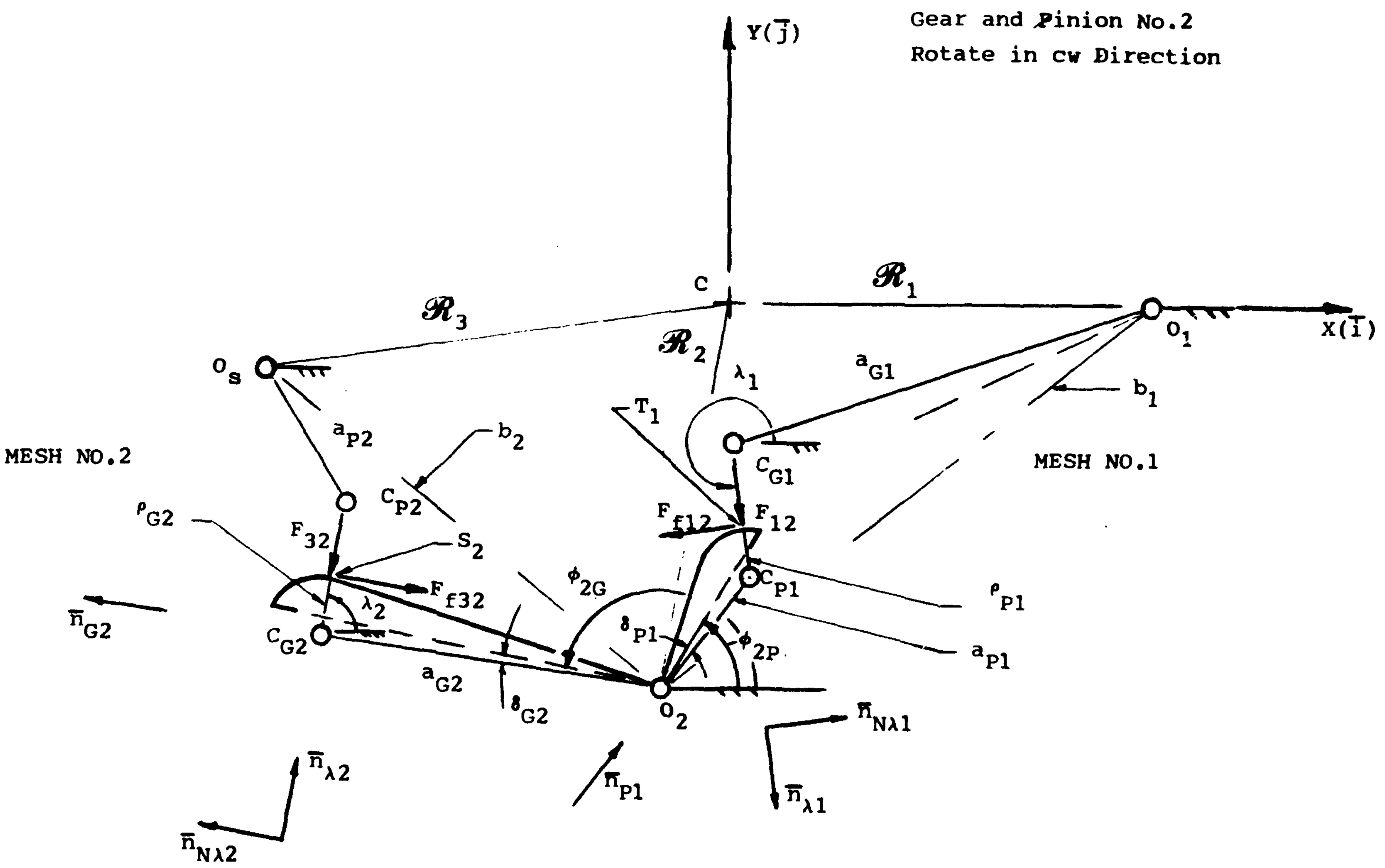


Figure D-14a. Top view of free body diagram of gear and pinion no. 2. Mesh no. 2 is in round-on-round contact and mesh no. 1 is in round-on-round contact.

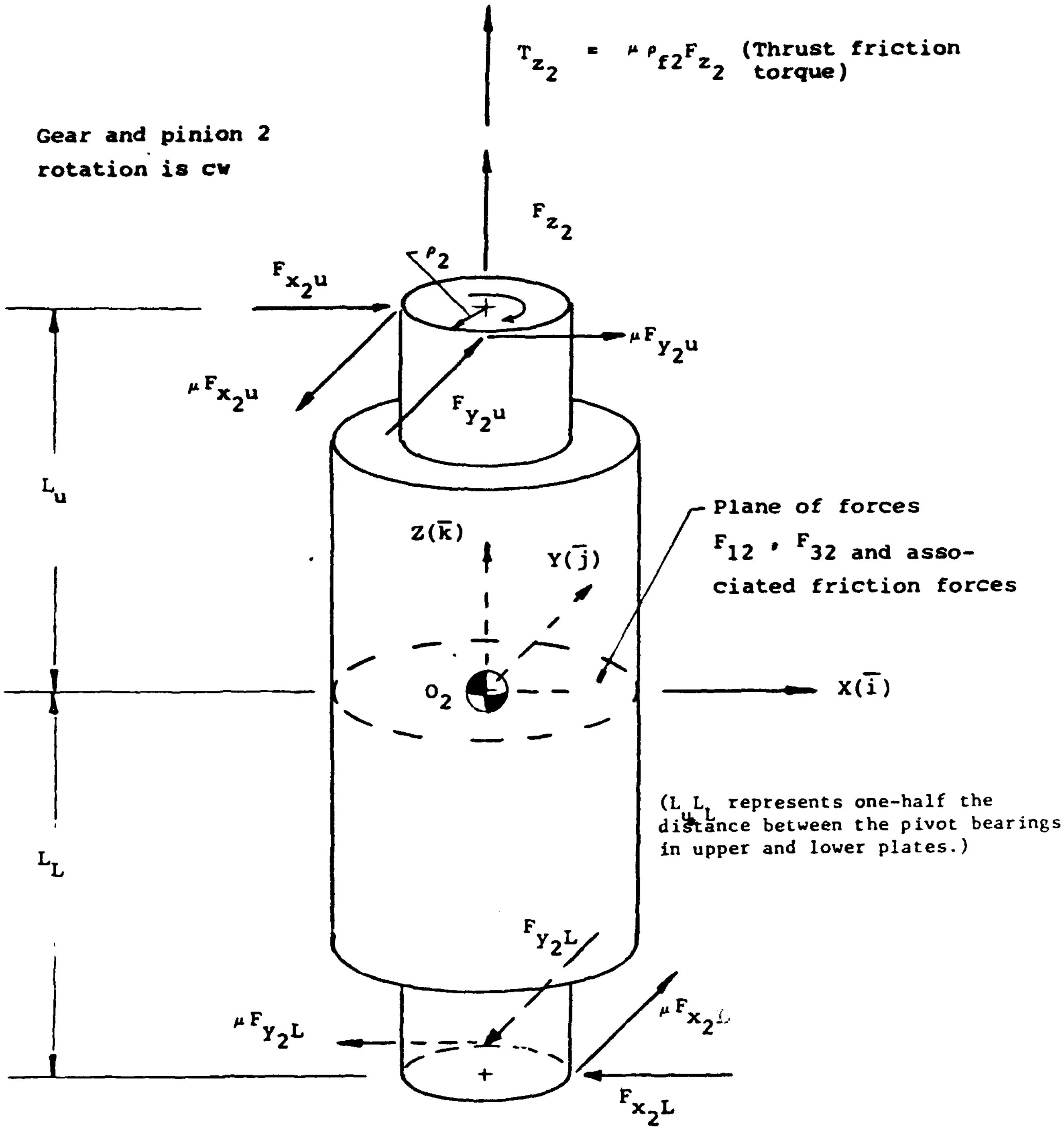


Figure D-14b. Gear pinion no. 2. Normal forces, friction forces, and thrust friction torque on pivots. (Same for all types of mesh combinations.)

The full force equation is now obtained with the help of figures D-14a and D-14b, as well as equations D-609 to D-612

$$-F_{23}\bar{n}_{\lambda 2} - s_{2R}\mu F_{23}\bar{n}_{N\lambda 2} + F_{12}\bar{n}_{\lambda 1} + \mu s_{1R}F_{12}\bar{n}_{N\lambda 1}$$

$$+ F_{x2u}\bar{i} - \mu F_{x2u}\bar{j} + F_{y2u}\bar{j} + \mu F_{y2u}\bar{i} + F_{z2}\bar{k}$$

$$- F_{x2L}\bar{i} + \mu F_{x2L}\bar{j} - F_{y2L}\bar{j} - \mu F_{y2L}\bar{i} = m_2 (Q_x\bar{i} + Q_y\bar{j} + Q_z\bar{k}) \quad \text{(D-614)}$$

In the above, $\bar{n}_{\lambda 2}$ and $\bar{n}_{N\lambda 2}$ are given by equations D-145b and D-147, respectively. The unit vectors $\bar{n}_{\lambda 1}$ and $\bar{n}_{N\lambda 1}$ were defined by equations D-427 and D-429. Appropriate substitution and subsequent separation into x and y components furnishes

X-Component of Force Equation

$$-F_{23} \cos \lambda_2 + \mu s_{2R}F_{23} \sin \lambda_2 + F_{12} \cos \lambda_1 - \mu s_{1R}F_{12} \sin \lambda_1$$

$$+ F_{x2u} + \mu F_{y2u} - F_{x2L} - \mu F_{y2L} = m_2 Q_x \quad \text{(D-615)}$$

Y-Component of Force Equation

$$-F_{23} \sin \lambda_2 - \mu s_{2R}F_{23} \cos \lambda_2 + F_{12} \sin \lambda_1 + \mu s_{1R}F_{12} \cos \lambda_1$$

$$- \mu F_{x2u} + F_{y2u} + \mu F_{x2L} - F_{y2L} = m_2 Q_y \quad \text{(D-616)}$$

Z-Component of Force Equation

This thrust force is best expressed in tilded form, so that,

$$\tilde{F}_{z2} = | m_2 Q_z | \quad \text{(D-617)}$$

Moment Equations

Since gear and pinion no. 2 represents a symmetrical body without products of inertia, its moment equation may be expressed in terms of the projectile-fixed X-Y-Z system by the appropriate adaptation of equation B-13 of appendix B.

The angular velocity $\dot{\phi}_2$ and the angular acceleration $\ddot{\phi}_2$, of gear and pinion no. 2 with respect to the projectile must eventually be expressed in terms of the escape wheel angular velocity $\dot{\phi}$ and angular acceleration $\ddot{\phi}$ in such a way that the round-on-round contact of mesh no. 2 is taken into account.

This gives the moment equation the following form (note that the pivot point O_2 and the center of mass C_2 coincide)

$$\overline{M}_{O_2} = \left[I_{x2}\dot{\omega}_x + I_{z2}\omega_y\left(\omega_z + \dot{\phi}_2\right) - I_{y2}\omega_y\omega_z\right]\bar{i}$$

$$+\left[I_{y2}\dot{\omega}_y + I_{x2}\omega_x\omega_z - I_{z2}\omega_x\left(\omega_z + \dot{\phi}_2\right)\right]\bar{j} + I_{z2}\left(\dot{\omega}_z + \ddot{\phi}_2\right)\bar{k} \qquad \text{(D-618)}$$

The moment $\overline{M}_{O_2}$ about point O_2 is now found with the help of the pivot shaft free-body diagram of figures D-14a and D-14b. Note that the thrust torque $\mu\rho_{z2}\tilde{F}_{z2}\bar{k}$ uses the tilded form of F_{z2} of equation D-617 in order to always make this friction moment positive, i.e., oppose the clockwise rotation of the component. The parameter ρ_{f2} represents the thrust friction radius, while ρ_2 is the radius of the pivot shaft. Then

$$\overline{M}_{O_2} = (a_{G2}\bar{n}_{G2} + \rho_{G2}\bar{n}_{\lambda2}) \times (-F_{23}\bar{n}_{\lambda2} - \mu s_{2R}F_{23}\bar{n}_{N\lambda2})$$

$$+ (a_{P1}\bar{n}_{P1} - \rho_{P1}\bar{n}_{\lambda1}) \times (F_{12}\bar{n}_{\lambda1} + \mu s_{1R}F_{12}\bar{n}_{N\lambda1})$$

$$+ \mu\rho_{f2}\tilde{F}_{z2}\bar{k} + \left(L_u\bar{k} - \rho_2\bar{i}\right) \times \left(F_{x2u}\bar{i} - \mu F_{x2u}\bar{j}\right)$$

$$+ \left(L_u\bar{k} - \rho_2\bar{j}\right) \times \left(F_{y2u}\bar{j} + \mu F_{y2u}\bar{i}\right) + \left(-L_L\bar{k} + \rho_2\bar{i}\right) \times \left(-F_{x2L}\bar{i} + \mu F_{x2L}\bar{j}\right)$$

$$+ \left(-L_L\bar{k} + \rho_2\bar{j}\right) \times \left(-F_{y2L}\bar{j} - \mu F_{y2L}\bar{i}\right) \qquad \text{(D-619)}$$

With equations G-2, G-3, G-4 and G-47, G-48, G-49 of ref 5, the above becomes

$$\overline{M}_{O_2} = [\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} + L_L F_{y2L}]\bar{i} + [L_u F_{x2u}$$

$$+ \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L}]\bar{j} + \left[F_{23}\left\{a_{G2}\left(\sin\left(\phi_{2G} + \delta_{G2} - \lambda_1\right)\right.\right.\right.$$

$$\left.\left.- \mu s_{2R}\cos\left(\phi_{2G} + \delta_{G2} - \lambda_2\right)\right) - \mu\rho_{G2}s_{2R}\right\} + F_{12}\left\{a_{P1}\left(-\sin\left(\phi_{2P} - \delta_{P1} - \lambda_1\right)\right.\right.$$

$$\left.\left.+ \mu s_{1R}\cos\left(\phi_{2P} - \delta_{P1} - \lambda_1\right)\right) - \mu\rho_{P1}s_{1R}\right\} + \mu\rho_{F2}\tilde{F}_{z2}$$

$$\left.+ \mu\rho_2\left(F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L}\right)\right]\bar{k} \qquad \text{(D-620)}$$

Substitution of equation D-260 into equation D-618 yields the following moment component expressions

X-Component of Gear and Pinion Moment Equation

$$\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L} = I_{x2}\dot{\omega}_x + I_{z2}\omega_y\left(\omega_z + \dot{\phi}_2\right) - I_{y2}\omega_y\omega_z \qquad \text{(D-621)}$$

Y-Component of Gear and Pinion Moment Equation

$$L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L} = I_{y2}\dot{\omega}_y + I_{x2}\omega_x\omega_z - I_{z2}\omega_x\left(\omega_z + \dot{\phi}_2\right) \qquad \text{(D-622)}$$

Z-Component of Gear and Pinion Moment Equation

$$F_{23}\left[a_{G2}\left(\sin\left(\phi_{2G} + \delta_{G2} - \lambda_2\right) - \mu s_{2R}\cos\left(\phi_{2G} + \delta_{G2} - \lambda_2\right)\right) - \mu\rho_{G2}s_{2R}\right]$$

$$+ F_{12}\left[a_{P1}\left(-\sin\left(\phi_{2P} - \delta_{P1} - \lambda_1\right) + \mu s_{1R}\cos\left(\phi_{2P} - \delta_{P1} - \lambda_1\right)\right) - \mu\rho_{P1}s_{1R}\right]$$

$$+ \mu\rho_{f2}\widetilde{F}_{z2} + \mu\rho_2\left(F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L}\right) = I_{z2}\left(\dot{\omega}_z + \ddot{\phi}_2\right) \qquad \text{(D-623)}$$

Simplification of Force and Moment Equations and Determination of Pivot Forces of Gear and Pinion No. 2

X-Component of the Force Equation

Equation D-615 is now rewritten

$$-F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} = A_{84RR}F_{23} + A_{85RR}F_{12} + A_{86} \qquad \text{(D-624)}$$

where

$$A_{84RR} = -\left(\cos\lambda_2 + \mu s_{2R}\sin\lambda_2\right) \qquad \text{(D-625)}$$

$$A_{85RR} = \cos\lambda_1 - \mu s_{1R}\sin\lambda_1 \qquad \text{(D-626)}$$

$$A_{86} = -M_2Q_x \qquad \text{(D-627)}$$

Y-Component of the Force Equation

Equation D-616 is rewritten

$$\mu F_{x2u} - F_{y2u} - \mu F_{x2L} + F_{y2L} = A_{87RR}F_{23} + A_{88RR}F_{12} + A_{89} \tag{D-628}$$

where

$$A_{87RR} = -\left(\sin\lambda_2 + \mu s_{2R}\cos\lambda_2\right) \tag{D-629}$$

$$A_{88RR} = \sin\lambda_1 + \mu s_{1R}\cos\lambda_1 \tag{D-630}$$

$$A_{89} = -m_2 Q_y \tag{D-631}$$

The Z-component of the force equation remains as in equation D-617.

X-Component of the Moment Equation

Equation D-621 is rewritten

$$-\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = A_{90} + A_{91}\dot{\phi}_2 \tag{D-632}$$

where

$$A_{90} = -\left[I_{x2}\dot{\omega}_x + \omega_y\omega_z\left(I_{z2} - I_{y2}\right)\right] \tag{D-633}$$

$$A_{91} = -I_{z2}\omega_y \tag{D-634}$$

Y-Component of the Moment Equation

Equation D-622 is rewritten

$$-L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} = A_{92} + A_{93}\dot{\phi}_2 \tag{D-635}$$

where

$$A_{92} = -\left[I_{y2}\dot{\omega}_y + \omega_x\omega_z\left(I_{x2} - I_{z2}\right)\right] \tag{D-636}$$

$$A_{93} = I_{z2}\omega_x \tag{D-637}$$

Equation D-623 for the Z-component of the moment remains as is.

Simultaneous Solution of Pivot Forces. Equations D-624, D-628, D-632, and D-635 are now solved simultaneously for the pivot forces. Therefore

$$\left.\begin{aligned}
&-F_{x2u} - \mu F_{y} \quad\quad {}_{x2L} + \mu F_{y2L} = B_{21} \\
&\mu F_{x2u} - F_{y2u} - \mu F_{x2L} + F_{y2L} = B_{22} \\
&-\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = B_{23} \\
&-L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} = B_{24}
\end{aligned}\right\} \qquad \text{(D-638)}$$

where

$$B_{21} = A_{84RR}F_{23} + A_{85RR}F_{1} \quad \text{(D-639)}$$

$$B_{22} = A_{87RR}F_{23} + A_{88RR}F_{12} + A \quad \text{(D-640)}$$

$$B_{23} = A_{90} + A_{91}\dot{\phi}_2 \quad \text{(D-641)}$$

$$B_{24} = A_{92} + A_{93}\dot{\phi}_2 \quad \text{(D-642)}$$

NOTE: Since the B_{2i} fo not appear in the computer program, their subscripts will not be adjusted for the various mesh contact modes. Only the A's and C's will reflect these variations.

To use the solutions of equation D-67, equation D-638 has to be changed to a form that has the same signs as this set of expressions. This may be accomplished by substituting

$$\mu^* = -\mu \quad \text{(D-643)}$$

(This replaces $A_{11} = \mu_1 s_5$ in equation D-67.) Equation D-638 then becomes

$$\left.\begin{aligned}
&-F_{x2u} + \mu^* F_{y2u} + F_{x2L} - \mu^* F_{y2L} = B_{21} \\
&-\mu^* F_{x2u} - F_{y2u} + \mu^* F_{x2L} + F_{y2L} = B_{22} \\
&\mu^* L_u F_{x2u} + L_u F_{y2u} + \mu^* L_L F_{x2L} + L_L F_{y2L} = B_{23} \\
&-L_u F_{x2u} + \mu^* L_u F_{y2u} - L_L F_{x2L} + \mu^* L_L F_{y2L} = B_{24}
\end{aligned}\right\} \qquad \text{(D-644)}$$

With the above substitution (i.e., eq D-643) the coefficient determinant of equation D-644 becomes according to equation D-75

$$D = \left[(L_u + L_L)(1 + \mu^2) \right]^2 \quad \text{(D-645)}$$

According to equation D-80, the determinant $D_{F_{x2u}}$ now becomes with the appropriate changes

$$D_{F_{x2u}} = (L_u + L_L)(1 + \mu^2)[-L_L B_{21} + \mu L_L B_{22} - \mu B_{23} - B_{24}] \qquad \text{(D-646)}$$

Now substitute for the B_{2i}'s according to equations D-639 to D-642

$$D_{F_{x2u}} = (L_u + L_L)(1 + \mu^2)\{-L_L[A_{84RR}F_{23} + A_{85RR}F_{12} + A_{86}]$$

$$+ \mu L_L[A_{87RR}F_{23} + A_{88RR}F_{12} + A_{89}]$$

$$- \mu[A_{90} + A_{91}\dot{\phi}_2] - [A_{92} + A_{93}\dot{\phi}_2]\} \qquad \text{(D-647)}$$

After collecting of terms, the tilded force $\tilde{F}_{x2u}$ becomes

$$\tilde{F}_{x2u} = \frac{\tilde{D}_{F_{x2u}}}{D} = \frac{1}{L_T(1 + \mu^2)}[C_{57} + C_{58}\,\dot{\phi}_2 + C_{59RR}F_{23} + C_{60RR}F_{12}] \qquad \text{(D-648)}$$

where

$$C_{57} = |-L_L A_{86} + \mu(L_L A_{89} - A_{90}) - A_{92}| \qquad \text{(D-649)}$$

$$C_{58} = |\mu A_{91} + A_{93}| \qquad \text{(D-650)}$$

$$C_{59RR} = |L_L(\mu A_{87RR} - A_{84RR})| \qquad \text{(D-651)}$$

$$C_{60RR} = |L_L(\mu A_{88RR} - A_{85RR})| \qquad \text{(D-652)}$$

According to equation D-90, $D_{F_{y2u}}$ with appropriate changes becomes

$$D_{F_{y2u}} - (L_u + L_L)(1 + \mu^2)[-\mu L_L B_{21} - L_L B_{22} + B_{23} - \mu B_{24}] \qquad \text{(D-653)}$$

Substitution of equations D-639 to D-642 gives

$$D_{F_{y2u}} - (L_u + L_L)(1 + \mu^2)\{-\mu L_L[A_{84RR}F_{23} + A_{85RR}F_{12} + A_{86}]$$

$$-L_L[A_{87RR}F_{23} + A_{88RR}F_{12} + A_{89}]$$

$$+ [A_{90} + A_{91}\dot{\phi}_2] - \mu[A_{92} + A_{93}\dot{\phi}_2] \tag{D-654}$$

After appropriate collecting of terms, the tilded force $\widetilde{F}_{y2u}$ **becomes**

$$\widetilde{F}_{y2u} = \frac{\widetilde{D}_{F_{y2u}}}{D} = \frac{1}{L_T(1+\mu^2)}[C_{61} + C_{62}\,\dot{\phi}_2 + C_{63RR}F_{23} + C_{64RR}F_{12}] \tag{D-655}$$

where

$$C_{61} = |-L_L A_{89} - \mu(L_L A_{86} + A_{92}) + A_{90}| \tag{D-656}$$

$$C_{62} = |A_{91} - \mu A_{93}| \tag{D-657}$$

$$C_{63RR} = |L_L(\mu A_{84RR} + A_{87RR})| \tag{D-658}$$

$$C_{64RR} = |L_L(\mu A_{85RR} + A_{88RR})| \tag{D-659}$$

According to equation D-100, $D_{F_{x2L}}$ with the applicable changes becomes

$$D_{F_{x2L}} = (L_u + L_L)(1+\mu^2)\{L_u B_{21} - \mu L_u B_{22} - \mu B_{23} - B_{24}\} \tag{D-660}$$

Substitute equations D-639 to D-642

$$D_{F_{x2L}} = (L_u + L_L)(1+\mu^2)\{L_u[A_{84RR}F_{23} + A_{85RR}F_{12} + A_{86}]$$

$$- \mu L_u[A_{87RR}F_{23} + A_{88RR}F_{12} + A_{89}]$$

$$- \mu[A_{90} + A_{91}\dot{\phi}] - [A_{92} + A_{93}\dot{\phi}_2]\} \tag{D-661}$$

After collecting of terms, the tilded force F_{x2L} becomes

$$\widetilde{F}_{x2L} = \frac{\widetilde{D}_{F_{x2L}}}{D} = \frac{1}{L_T(1+\mu^2)}[C_{65} + C_{66}\,\dot{\phi}_2 + C_{67RR}F_{23} + C_{68RR}F_{12}] \tag{D-662}$$

where

$$C_{65} = |-\mu(L_u A_{89} + A_{90}) + L_U A_{86} - A_{92}| \tag{D-663}$$

$$C_{66} = |\mu A_{91} + A_{93}| \tag{D-664}$$

$$C_{67RR} = \left|L_u\left(A_{84RR} - \mu A_{87RR}\right)\right| \tag{D-665}$$

$$C_{68RR} = \left|L_u\left(A_{85RR} - \mu A_{88RR}\right)\right| \tag{D-666}$$

According to equation D-109, the determinant $D_{F_{y2L}}$ after applicable adaption becomes

$$D_{F_{y2L}} = (L_u + L_L)\left(1 + \mu^2\right)\left\{\mu L_u B_{21} + L_u B_{22} + B_{23} - \mu B_{24}\right\} \tag{D-667}$$

Substitution of equations D-639 to D-642 leads to

$$\begin{aligned} D_{F_{y2L}} = (L_u + L_L)\left(1 + \mu^2\right)\{&\mu L_u [A_{84RR}F_{23} + A_{85RR}F_{12} + A_{86}] \\ &+ L_u [A_{87RR}F_{23} + A_{88RR}F_{12} + A_{89}] \\ &+ [A_{90} + A_{91}\dot{\phi}_2] - \mu[A_{92} + A_{93}\dot{\phi}_2]\,\} \end{aligned} \tag{D-668}$$

Again, terms are collected and an expression for the tilded force F_{y2L} is found. Therefore

$$\tilde{F}_{y2L} = \frac{\tilde{D}_{F_{y2L}}}{D} = \frac{1}{L_T\left(1 + \mu^2\right)}\left[C_{69} + C_{70}\dot{\phi}_2 + C_{71RR}F_{23} + C_{72RR}F_{12}\right] \tag{D-669}$$

where

$$C_{69} = \left|L_u A_{89} + \mu(L_u A_{86} - A_{92}) + A_{90}\right| \tag{D-670}$$

$$C_{70} = |A_{91} - \mu A_{93}| \tag{D-671}$$

$$C_{71RR} = \left|L_u\left(\mu A_{84RR} + A_{87RR}\right)\right| \tag{D-672}$$

$$C_{72RR} = \left|L_u\left(\mu A_{85RR} + A_{88RR}\right)\right| \tag{D-673}$$

Determination of Contact Force $\bar{F}_{23}$ in Terms of Contact Force $\bar{F}_{12}$ and Gear and Pinion No. 2 Parameters with Both Meshes in Round-on-Round Contact

Substitution of equations D-648, D-655, D-662, D-669, and D-617 into the Z-moment equation D-623 is now required. First, let the tilded forces be added

$$\tilde{F}_{x2u} + \tilde{F}_{y2u} + \tilde{F}_{x2L} + \tilde{F}_{y2L} = A_{94} + A_{95}\dot{\phi} + A_{96RR}F_{23} + A_{97RR}F_{12} \quad \text{(D-674)}$$

where

$$A_{94} = \frac{C_{57} + C_{61} + C_{65} + C_{69}}{L_T(1 + \mu^2)} \quad \text{(D-675)}$$

$$A_{95} = \frac{C_{58} + C_{62} + C_{66} + C_{70}}{L_T(1 + \mu^2)} \quad \text{(D-676)}$$

$$A_{96RR} = \frac{C_{59RR} + C_{63RR} + C_{67RR} + C_{71RR}}{L_T(1 + \mu^2)} \quad \text{(D-677)}$$

$$A_{97RR} = \frac{C_{60RR} + C_{64RR} + C_{68RR} + C_{72RR}}{L_T(1 + \mu^2)} \quad \text{(D-678)}$$

Further, let equation D-617 be expressed as

$$\tilde{F}_{z2} = A_{98} = |m_2 Q_z| \quad \text{(D-679)}$$

Equation D-623 then becomes

$$\begin{aligned}
&F_{23}[a_{G2}(\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R}\cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu\rho_{G2}s_{2R}] \\
&+ F_{12}[a_{P1}(-\sin(\phi_{2P} - \delta_{P1} - \lambda_1) + \mu s_{1R}\cos(\phi_{2P} - \delta_{P1} - \lambda_1)) - \mu\rho_{P1}s_{1R}] \\
&+ \mu\rho_{12}A_{98} + \mu\rho_2\,[A_{94} \pm A_{95}\dot{\phi}_2 + A_{96RR}F_{23} + A_{97RR}F_{12}] \\
&= I_{z2}\left(\dot{\omega}_z + \ddot{\phi}\right)
\end{aligned} \quad \text{(D-680)}$$

or

$$F_{23}[a_{G2}(\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R}\cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu\rho_{G2}s_{2R} + \mu\rho_2 A_{96RR}]$$

$$+ F_{12}[a_{P1}(-\sin(\phi_{2P} - \delta_{P1} - \lambda_1) + \mu s_{1R}\cos(\phi_{2P} - \delta_{P1} - \lambda_1)) - \mu\rho_{P1}s_{1R} + \mu\rho_2 A_{97RR}]$$

$$+ \mu[\rho_{t2}A_{98} + \rho_2 A_{94}] \pm \mu\rho_2 A_{95}\dot{\phi}_2 = A_{99} + A_{100}\ddot{\phi}_2 \qquad \text{(D-681)}$$

where

$$A_{99} = I_{z2}\dot{\omega}_z \qquad \text{(D-682)}$$

$$A_{100} = I_{z2} \qquad \text{(D-683)}$$

Now consider again the signs of the friction moment terms, recalling that a reversal in the gear train motion will cause a change of the sign of μ in the program. The component rotates normally in a clockwise direction and the following friction moments must be positive.

$$\mu F_{23}\rho_2 A_{96RR} \; (A_{96RR} \text{ is sum of absolute values}) \qquad \text{(D-684)}$$

$$\mu F_{12}\rho_2 A_{97RR} \; (A_{97RR} \text{ is sum of absolute values}) \qquad \text{(D-685)}$$

$$\mu[\rho_{t2}A_{98} + \rho_2 A_{94}] \; (A_{94} \text{ and } A_{98} \text{ are absolute values}) \qquad \text{(D-686)}$$

The moment represented by the term containing $\dot{\phi}_2$ must always act opposite to the direction of rotation of gear and pinion no. 2. Therefore, the term must have a negative sign and the absolute value of μ must be used

$$-|\mu|\rho_2 A_{95}\dot{\phi}_2 \qquad \text{(D-687)}$$

Note that A_{95} is an absolute value.

With the above considerations, equation D-681 becomes

$$F_{23}[a_{G2}(\sin(\phi_{2G} + \delta_{G2} - \lambda_1) - \mu s_{2R}\cos(\phi_{2G} + \delta_{2G} - \lambda_2)) - \mu\rho_{G2}s_{2R} + \mu\rho_2 A_{96RR}]$$

$$+ F_{12}[a_{P1}(-\sin(\phi_{2P} - \delta_{P1} - \lambda_1) + \mu s_{1R}\cos(\phi_{2P} - \delta_{P1} - \lambda_1)) - \mu\rho_{P1}s_{1R} + \mu\rho_2 A_{97RR}]$$

$$+ \mu[\rho_{t2}A_{98} + \rho_2 A_{94}] - |\mu|\rho_2 A_{95}\dot{\phi}_2 = A_{99} + A_{100}\ddot{\phi}_2 \qquad \text{(D-688)}$$

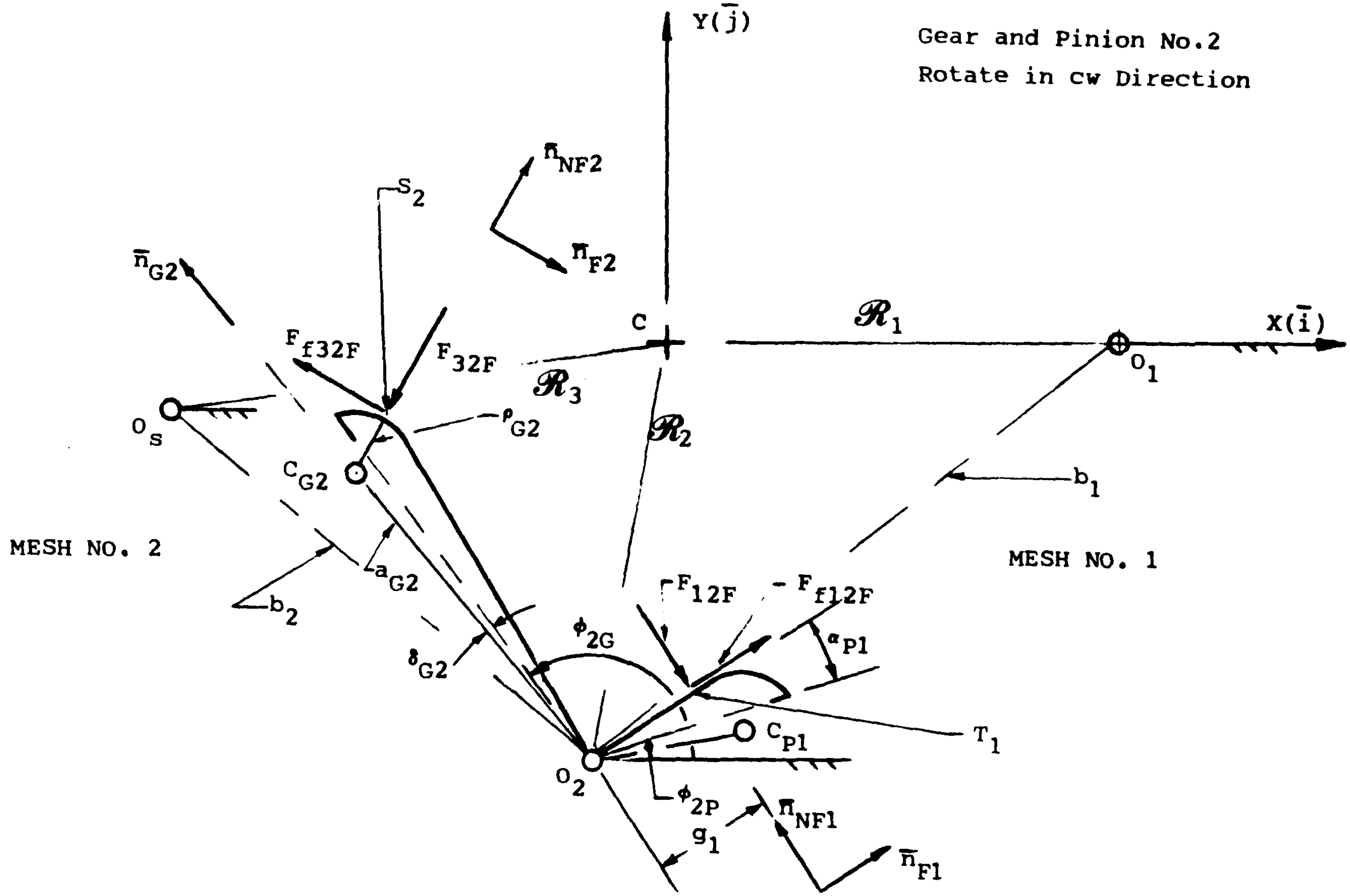


Figure D-15. Top view of free body diagram of gear and pinion no. 2. Mesh no. 2 is in round on flat contact and mesh no. 2 is in round-on-flat contact

Finally, the above is solved for F_{23}

$$F_{23} = \frac{A_{102RR} F_{12} - A_{103} + A_{104} \dot{\phi}_2 + A_{99} + A_{100} \ddot{\phi}_2}{A_{101RR}} \qquad \text{(D-689)}$$

where

$$A_{101RR} = a_{G2}(\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R} \cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu \rho_{G2} s_{2R} + \mu \rho_2 A_{96RR} \qquad \text{(D-690)}$$

$$A_{102RR} = -[a_{P1}(-\sin(\phi_{2P} - \delta_{P1} - \lambda_1) + \mu s_{1R} \cos(\phi_{2P} - \delta_{P1} - \lambda_1)) - \mu \rho_{P1} s_{1R} + \mu \rho_2 A_{97RR}] \qquad \text{(D-691)}$$

$$A_{103} = \mu[\rho_{f2} A_{98} + \rho_2 A_{94}] \qquad \text{(D-692)}$$

$$A_{104} = |\mu| \rho_2 A_{95} \qquad \text{(D-693)}$$

Dynamics of Gear and Pinion No. 2 with Mesh No. 2 and Mesh No. 1 in Round-on-Flat Contact

A schematic top view free body diagram of gear and pinion no. 2 with both meshes in the round-on-flat contact mode is shown in figure D-15. It shows the contact force

$$\bar{F}_{32F} = -\bar{F}_{23F} = -F_{23F} \bar{n}_{NF2} \qquad \text{(D-694)}$$

of pinion no. 3 on gear no. 2, opposite to force $\bar{F}_{23F}$, as given by equation D-245a. The associated friction force $\bar{F}_{f32F}$ is opposite to $\bar{F}_{f23F}$, as given by equation D-246. Thus

$$\bar{F}_{f32F} = -\bar{F}_{f23F} = -\mu s_{2F} F_{23F} \bar{n}_{F2} \qquad \text{(D-695)}$$

The contact force $\bar{F}_{12F}$ of gear no. 1 on pinion no. 2 is also shown in figure D-15. This force is opposite in direction to contact force $\bar{F}_{21F}$, which is given by equation D-538. Then

$$\bar{F}_{12F} = -\bar{F}_{21F} = -F_{12F} \bar{n}_{NF1} \qquad \text{(D-696)}$$

The associated friction force $\bar{F}_{f12F}$ is opposite in direction to the friction force $\bar{F}_{f12F}$ of equation D-540, i.e.

$$\bar{F}_{f12F} = -\bar{F}_{f21F} = \mu s_{1F} F_{12F} \bar{n}_{F1} \qquad \text{(D-697)}$$

Figure D-14b may also be used for the present case as a free body diagram of the pivot shaft of gear and pinion no. 2. As stated earlier, this representation of normal, friction and thrust forces and torques acting on the CW rotating component is valid regardless of the instantaneous combination of mesh contact modes.

Force Equations

The force equation is again based on Newton's law, i.e.

$$\Sigma\bar{F} = m_2\bar{A}_{O_2/ground} \tag{D-698}$$

where

$\Sigma\bar{F}$ = Sum of the pivot forces as well as the various contact forces

m_2 = Mass of gear and pinion no. 2

$\bar{A}_{O_2/ground}$ = Acceleration of the component center of mass, i.e., equation D-605

The full force equation is now obtained with the help of figures D-15 and D-14b, as well as equations D-694 to D-697

$$-F_{23F}\bar{n}_{NF2} - \mu s_{2F}F_{23F}\bar{n}_{F2} - F_{12F}\bar{n}_{NF1} + \mu s_{1F}F_{12F}\bar{n}_{F1}$$

$$+ F_{x2u}\bar{i} - \mu F_{x2u}\bar{j} + F_{y2u}\bar{j} + \mu F_{y2u}\bar{i} + F_{z2}\bar{k}$$

$$- F_{x2L}\bar{i} + \mu F_{x2L}\bar{j} - F_{y2L}\bar{j} - \mu F_{y2L}\bar{i} = m_2(Q_x\bar{i} + Q_y\bar{j} + Q_z\bar{k}) \tag{D-699}$$

In the above, $\bar{n}_{NF2}$ and $\bar{n}_{F2}$ are given by equations D-245b and D-247, respectively. The unit vectors $\bar{n}_{NF1}$ and $\bar{n}_{F1}$ were defined by equations D-539 and D-541.

Appropriate substitution and subsequent component separation furnished the following

<u>X-Component of Force Equation</u>

$$F_{23F}\sin(\phi_S - \alpha_{P2}) - \mu s_{2F}F_{23F}\cos(\phi_S - \alpha_{P2})$$

$$+ F_{12F}\sin(\phi_{2P} + \alpha_{P1}) + \mu s_{1F}F_{12F}\cos(\phi_{2P} + \alpha_{P1})$$

$$+ F_{x2u} + \mu F_{y2u} - F_{x2L} - \mu F_{y2L} = m_2Q_x \tag{D-700}$$

Y-Component of Force Equation

$$-F_{23F}\cos(\phi_S - \alpha_{P2}) - \mu s_{2F}F_{23F}\sin(\phi_s - \alpha_{P2})$$

$$-F_{12F}\cos(\phi_{2P} + \alpha_{P1}) + \mu s_{1F}F_{12F}\sin(\phi_{2P} + \alpha_{P1})$$

$$-\mu F_{x2u} + F_{y2u} + \mu F_{x2L} - F_{y2L} = m_2 Q_y \qquad \text{(D-701)}$$

Z-Component of Force Equation

This thrust force is best expressed in tilded form, so that,

$$\tilde{F}_{z2} = |m_2 Q_z| \qquad \text{(D-702)}$$

Moment Equations

Again, the moment equation is expressed in terms of the projectile-fixed coordinate system. The angular velocity $\dot{\phi}_2$ and the angular acceleration $\ddot{\phi}_2$ must now reflect the round-on-flat contact of mesh no. 2, when these quantities are expressed in terms of the escape wheel angular velocity and acceleration. With the above, equation D-618 is again applicable.

The expression for the moment $\overline{M}_{O2}$ is now found with the help of the free body diagrams of figures D-15 and D-14b. The remarks concerning the thrust friction torque, following equation D-618, still hold. Then

$$\overline{M}_{O2} = (a_{G2}\overline{n}_{G2} + \rho_{G2}\overline{n}_{NF2}) \times (-F_{23F}\overline{n}_{NF2} - \mu s_{2F}F_{23F}\overline{n}_{F2}) + g_1\overline{n}_{F1} \times (-F_{12F}\overline{n}_{NF1})$$

$$+ \mu\rho_{f2}\tilde{F}_{z2}\overline{k} + (L_u\overline{k} - \rho_2\overline{i}) \times (F_{x2u}\overline{i} - \mu F_{x2u}\overline{j}) + (L_u\overline{k} - \rho_2\overline{j}) \times (F_{y2u}\overline{j} + \mu F_{y2u}\overline{i})$$

$$+ (-L_L\overline{k} + \rho_2\overline{i}) \times (-F_{x2L}\overline{i} + \mu F_{x2L}\overline{j})$$

$$+ (-L_L\overline{k} + \rho_2\overline{j}) \times (-F_{y2L}\overline{j} - \mu F_{y2L}\overline{i}) \qquad \text{(D-703)}$$

The above becomes with equations G-22, G-23, G-47, G-64, and G-65 of ref 5

$$\overline{M}_{O2} = \left[\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L}\right] \bar{i}$$

$$+ \left[L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L}\right] \bar{j}$$

$$+ \left[F_{23F} \left\{a_{G2} \left(-\cos\left(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}\right)\right.\right.\right.$$

$$\left.\left. + \mu s_{2F} \sin\left(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}\right)\right) + \rho_{G2} \mu s_{2F}\right] - g_1 F_{12F}$$

$$+ \mu \rho_{12} \tilde{F}_{z2} + \mu \rho_2 \left(F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L}\right)\left.\right] \bar{k} \qquad \text{(D-704)}$$

Substitution of equation D-704 into equation D-618 yields the following moment component expressions.

X-Component of Gear and Pinion Moment Equation

$$\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L}$$

$$= I_{y2} \dot{\omega}_x + I_{z2} \omega_y \left(\omega_z + \dot{\phi}_2\right) - I_{y2} \omega_y \omega_z \qquad \text{(D-705)}$$

Y-Component of Gear and Pinion Moment Equation

$$L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L}$$

$$= I_{y2} \dot{\omega}_y + I_{x2} \omega_x \omega_z - I_{z2} \omega_x \left(\omega_z + \dot{\phi}_2\right) \qquad \text{(D-706)}$$

Z-Component of Gear and Pinion Moment Equation

$$F_{23F} \left\{a_{G2} \left(-\cos\left(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}\right) + \mu s_{2F} \sin\left(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}\right)\right)\right.$$

$$\left. + \rho_{G2} \mu s_{21F}\right\} - g_1 F_{12F} + \mu \rho_{12} \tilde{F}_{z2} + \mu \rho_2 \left(F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L}\right)$$

$$= I_{z2} \left(\dot{\omega}_z + \ddot{\phi}_2\right) \qquad \text{(D-707)}$$

Simplification of Force and Moment Equations and Determination of Pivot Forces on Gear and Pinion No. 2

X-Component of the Force Equation

Equation D-700 is now rewritten

$$-F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} = A_{84FF} F_{23F} + A_{85FF} F_{12F} + A_{86} \qquad \text{(D-708)}$$

where

$$A_{84FF} = \sin\left(\phi_s - \alpha_{P2}\right) - \mu s_{2F}\cos\left(\phi_s - \alpha_{P2}\right) \qquad \text{(D-709)}$$

$$A_{85FF} = \sin\left(\phi_{2P} + \alpha_{P1}\right) + \mu s_{1F}\cos\left(\phi_{2P} + \alpha_{P1}\right) \qquad \text{(D-710)}$$

$$A_{86} = -m_2 Q_x \qquad \text{(D-711)}$$

Y-Component of the Force Equation

Equation D-701 is rewritten

$$\mu F_{x2u} - F_{y2u} - F_{x2L} + F_{y2L} = A_{87FF}F_{23F} + A_{88FF}F_{12F} + A_{89} \qquad \text{(D-712)}$$

where

$$A_{87FF} = -\left(\cos\left(\phi_s - \alpha_{P2}\right) + \mu s_{2F}\sin\left(\phi_s - \alpha_{P2}\right)\right) \qquad \text{(D-713)}$$

$$A_{88FF} = -\cos\left(\phi_{2P} + \alpha_{P1}\right) + \mu s_{1F}\sin\left(\phi_{2P} + \alpha_{P1}\right) \qquad \text{(D-714)}$$

$$A_{89} = -m_2 Q_y \qquad \text{(D-715)}$$

The Z-component of the force equation remains as in equation D-702.

X-Component of the Moment Equation

Equation D-705 is rewritten

$$-\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = A_{90} + A_{91}\dot{\phi}_2 \qquad \text{(D-716)}$$

where

$$A_{90} = -\left[I_{x2}\dot{\omega}_x + \omega_y \omega_z \left(I_{z2} - I_{y2}\right)\right] \qquad \text{(D-717)}$$

$$A_{91} = -I_{z2}\omega_y \qquad \text{(D-718)}$$

Y-Component of the Moment Equation

Equation D-706 is rewritten

$$-L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} = A_{92} + A_{93}\dot{\phi}_2 \qquad \text{(D-719)}$$

where

$$A_{92} = -\left[I_{y2}\dot{\omega}_y + \omega_x\omega_z\left(I_{x2} - I_{z2}\right)\right] \quad \text{(D-720)}$$

$$A_{93} = I_{z2}\omega_z \quad \text{(D-721)}$$

Equation D-707 for the Z-component of the moment equation remains as is.

Simultaneous Solution of Pivot Forces. Equations D-708, D-712, D-716, and D-719 are now solved simultaneously for the pivot forces. Therefore,

$$\left.\begin{aligned}
&-F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} = B_{21} \\
&\mu F_{x2u} - F_{y2u} - \mu F_{x2L} + F_{y2L} = B_{22} \\
&-\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = B_{23} \\
&-L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} = B_{24}
\end{aligned}\right\} \quad \text{(D-722)}$$

where

$$B_{21} = A_{84FF}F_{23F} + A_{85FF}F_{12F} + A_{86} \quad \text{(D-723)}$$

$$B_{22} = A_{87FF}F_{23F} + A_{88FF}F_{12F} + A_{89} \quad \text{(D-724)}$$

$$B_{23} = A_{90} + A_{91}\dot{\phi}_2 \quad \text{(D-725)}$$

$$B_{24} = A_{92} + A_{93}\dot{\phi}_2 \quad \text{(D-726)}$$

As decided earlier, since the B_{2i} do not appear in the computer program, their subscripts will not be adjusted for the various mesh contact modes. Only the A's and C's will reflect these variations.

To use the solutions of equation D-67, equation D-722 has to be changed again to a form that has the same signs as this set of expressions. This may be accomplished by subsituting

$$\mu^* = -\mu \quad \text{(D-727)}$$

(This replaces $A_{11} = \mu_1 s_5$ in equation D-67.) Equation D-722 then becomes

$$\left.\begin{aligned}
&-F_{x2u} + \mu^* F_{y2u} + F_{x2L} - \mu^* F_{y2L} = B_{21} \\
&-\mu^* F_{x2u} - F_{y2u} + \mu^* F_{x2L} + F_{y2L} = B_{22} \\
&\mu^* L_u F_{x2u} + L_u F_{y2u} + \mu^* L_L F_{x2L} + L_L F_{y2L} = B_{23} \\
&-L_u F_{x2u} + \mu^* L_u F_{y2u} - L_L F_{x2L} + \mu^* L_L F_{y2L} = B_{24}
\end{aligned}\right\} \tag{D-728}$$

With the above substitution (i.e., equation D-727) the coeffici determinant of equation D-728 becomes according to equation D-75

$$D = \left[(L_u + L_L)\left(1 + \mu^2\right) \right]^2 \tag{D-729}$$

According to equation D-80, the determinant $D_{F_{x2u}}$ now becomes with the appropriate changes

$$D_{F_{x2u}} = (L_u + L_L)\left(1 + \mu^2\right)\left[-L_L B_{21} + \mu L_L B_{22} - \mu B_{23} - B_{24}\right] \tag{D-730}$$

Now substitute for the B_{2i}'s according to equations D-723 to D-726

$$\begin{aligned}
D_{F_{x2u}} = (L_u + L_L)\left(1 + \mu^2\right)\Big\{&-L_L\left[A_{84FF}F_{23F} + A_{85FF}F_{12} + A_{86}\right] \\
&+ \mu L_L\left[A_{87FF}F_{23F} + A_{88FF}F_{12F} + A_{89}\right] \\
&-\mu\left[A_{90} + A_{91}\dot{\phi}_2\right] - \left[A_{92} + A_{93}\dot{\phi}_2\right]\Big\}
\end{aligned} \tag{D-731}$$

After collecting the terms, the tilded force $\widetilde{F}_{x2u}$ becomes

$$\widetilde{F}_{x2u} = \frac{\widetilde{D}_{F_{x2u}}}{D} = \frac{1}{L_T\left(1 + \mu^2\right)}\left[C_{57} + C_{58}\dot{\phi}_2 + C_{59FF}F_{23F} + C_{60FF}F_{12F}\right] \tag{D-732}$$

where

$$C_{57} = \left|-L_L A_{86} + \mu(L_L A_{89} - A_{90}) - A_{92}\right| \tag{D-733}$$

$$C_{58} = \left|\mu A_{91} + A_{93}\right| \tag{D-734}$$

$$C_{59FF} = \left|L_L\left(\mu A_{87FF} - A_{84FF}\right)\right| \tag{D-735}$$

$$C_{60FF} = \left|L_L\left(\mu A_{88FF} - A_{85FF}\right)\right| \tag{D-736}$$

According to equation D-90, $D_{F_{y2u}}$ with appropriate changes becomes

$$D_{F_{y2u}} = (L_u + L_L)(1 + \mu^2)[-\mu L_L B_{21} - L_L B_{22} + B_{23} - \mu B_{24}] \tag{D-737}$$

Substitution of equations D-723 to D-726 gives

$$\begin{aligned} D_{F_{y2u}} = (L_u + L_L)(1 + \mu^2)\{&-\mu L_L [A_{84FF}F_{23F} + A_{85FF}F_{12F} + A_{86}] \\ &- L_L [A_{87FF}F_{23F} + A_{88FF}F_{12F} + A_{89}] \\ &+ [A_{90} + A_{91}\dot{\phi}_2] - \mu[A_{92} + A_{93}\dot{\phi}_2]\} \end{aligned} \tag{D-738}$$

After appropriate collecting of terms, the tilded force $\widetilde{F}_{y2u}$ becomes

$$\widetilde{F}_{y2u} = \frac{\widetilde{D}_{F_{y2u}}}{D} = \frac{1}{L_T(1 + \mu^2)}\left[C_{61} + C_{62}\dot{\phi}_2 + C_{63FF}F_{23F} + C_{64FF}F_{12F}\right] \tag{D-739}$$

where

$$C_{61} = |-L_L A_{89} - \mu(L_L A_{86} + A_{92}) + A_{90}| \tag{D-740}$$

$$C_{62} = |A_{91} - \mu A_{93}| \tag{D-741}$$

$$C_{63FF} = |L_L (\mu A_{84FF} + A_{87FF})| \tag{D-742}$$

$$C_{64FF} = |L_L (\mu A_{85FF} + A_{88FF})| \tag{D-743}$$

According to equation D-100, $D_{F_{x2L}}$ with the applicable changes becomes

$$D_{F_{x2L}} = (L_u + L_L)(1 + \mu^2)\{L_u B_{21} - \mu L_u B_{22} - \mu B_{23} - B_{24}\} \tag{D-744}$$

Substitute equations D-723 to D-726

$$\begin{aligned} D_{F_{x2L}} = (L_u + L_L)(1 + \mu^2)\{&L_u [A_{84FF}F_{23F} + A_{85FF}F_{12F} + A_{86}] \\ &- \mu L_u [A_{87FF}F_{23F} + A_{88FF}F_{12F} + A_{89}] \\ &- \mu [A_{90} + A_{91}\dot{\phi}_2] - [A_{92} + A_{93}\dot{\phi}_2]\} \end{aligned} \tag{D-745}$$

After collecting of terms, the tilded force $\tilde{F}_{x2L}$ becomes

$$\tilde{F}_{x2L} = \frac{\tilde{D}_{F_{x2L}}}{D} = \frac{1}{L_T(1+\mu^2)}[C_{65} + C_{66}\,\dot{\phi}_2 + C_{67FF}F_{23} + C_{68FF}F_{12F}] \tag{D-746}$$

where

$$C_{65} = |-\mu(L_uA_{89} + A_{90}) + L_uA_{86} - A_{92}| \tag{D-747}$$

$$C_{66} = |\mu A_{91} + A_{93}| \tag{D-748}$$

$$C_{67FF} = |L_u(A_{84FF} - \mu A_{87FF})| \tag{D-749}$$

$$C_{68FF} = |L_u(A_{85FF} - \mu A_{88FF})| \tag{D-750}$$

According to equation D-109, the determinant $D_{F_{y2L}}$ after applicable adaptation becomes

$$D_{F_{y2L}}(L_u + L_L)(1+\mu^2)\{\mu L_uB_{21} + L_uB_{22} + B_{23} - \mu B_{24}\} \tag{D-751}$$

Substitution of equations D-723 to D-726 leads to

$$\begin{aligned} D_{F_{y2L}} = (L_u + L_L)(1+\mu^2)\{&\mu L_u[A_{84FF}F_{23F} + A_{85FF}F_{12F} + A_{86}] \\ &+ L_u[A_{87FF}F_{23F} + A_{88FF}F_{12F} + A_{89}] \\ &+ [A_{90} + A_{91}\dot{\phi}_2] - \mu[A_{92} + A_{93}\dot{\phi}_2]\} \end{aligned} \tag{D-752}$$

Again, terms are collected and an expression for the tilded force $\tilde{F}_{y2L}$ is found. Therefore

$$\tilde{F}_{y2L} = \frac{\tilde{D}_{F_{y2L}}}{D} = \frac{1}{L_T(1+\mu^2)}[C_{69} + C_{70}\dot{\phi}_2 + C_{71FF}F_{23F} + C_{72FF}F_{12F}] \tag{D-753}$$

where

$$C_{69} = |L_uA_{89} + \mu(L_uA_{86} - A_{92}) + A_{90}| \tag{D-754}$$

$$C_{70} = |A_{91} - \mu A_{93}| \tag{D-755}$$

$$C_{71FF} = |L_u(\mu A_{84FF} + A_{87FF})| \tag{D-756}$$

$$C_{72FF} = |L_u(\mu A_{85FF} + A_{88FF})| \tag{D-757}$$

Determination of Contact Force F_{23F} in Terms of Contact Force F_{12F} and Gear and Pinion No. 2 Parameters with Both Meshes in Round-on-Flat Contact

Substitution of equations D-732, D-739, D-746, D-753, and D-702 into the Z-moment equation D-701 is now required. First, let the tilded forces be added

$$\tilde{F}_{x2u} + \tilde{F}_{y2u} + \tilde{F}_{x2L} + \tilde{F}_{y2L} = A_{94} + A_{95}\dot{\phi} + A_{96FF}F_{23F} + A_{97FF}F_{12F} \tag{D-758}$$

where

$$A_{94} = \frac{C_{57} + C_{61} + C_{65} + C_{69}}{L_T(1 + \mu^2)} \tag{D-759}$$

$$A_{95} = \frac{C_{58} + C_{62} + C_{66} + C_{70}}{L_T(1 + \mu^2)} \tag{D-760}$$

$$A_{96FF} = \frac{C_{59FF} + C_{63FF} + C_{67FF} + C_{71FF}}{L_T(1 + \mu^2)} \tag{D-761}$$

$$A_{97FF} = \frac{C_{60FF} + C_{64FF} + C_{68FF} + C_{72FF}}{L_T(1 + \mu^2)} \tag{D-762}$$

Further, let equation D-702 be expressed as

$$F'_{z2} = A_{98} = |m_2Q_z| \tag{D-763}$$

Equation D-707 then becomes

$$\begin{aligned} &F_{23F}\{a_{G2}(-\cos(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2}) + \mu s_{2F}\sin(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2})) \\ &+\mu\rho_{G2}s_{2F}\} - g_1F_{12F} + \mu\rho_{12}A_{98} + \mu\rho_2\,[A_{94} \pm A_{95}\dot{\phi}_2 + A_{96FF}F_{23F} + A_{97FF}F_{12F}] \\ &= I_{z2}(\dot{\omega}_z + \ddot{\phi}_2) \end{aligned} \tag{D-764}$$

or

$$F_{23}[a_{G2}(-\cos(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2}) + \mu s_{2F}\sin(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2}))$$

$$+ \mu s_{2F}\rho_{G2} + \mu\rho_2 A_{96FF}] - F_{12F}[g_1 - \mu\rho_2 A_{97FF}]$$

$$+ \mu[\rho_{f2}A_{98} + \rho_2 A_{94}] \pm \mu\rho_2 A_{95}\dot{\phi}_2 = A_{99} + A_{100}\ddot{\phi}_2 \qquad \text{(D-765)}$$

where again, as in equations D-682 and D-683

$$A_{99} = I_{z2}\dot{\omega}_z \qquad \text{(D-766)}$$

$$A_{100} = I_{z2} \qquad \text{(D-767)}$$

Now consider again the signs of the friction moment terms, recalling that a reversal in the gear train motion will cause a change of the sign of μ in the program. The component rotates normally in a clockwise direction and the following friction moments msut be positive.

$\mu F_{23}\rho_2 A_{96FF}$ (A_{96FF} is the sum of absolute values) (D-768)

$\mu F_{12}\rho_2 A_{97FF}$ (A_{97FF} is the sum of absolute values) (D-769)

$\mu[\rho_{f2}A_{98} + \rho_2 A_{94}]$($A_{94}$ and A_{98} are absolute values) (D-770)

The moment represented by the term containing $\dot{\phi}_2$ must always act opposite to the direction of rotation of gear and pinion no. 2. Therefore the term must have a negative sign and the absolute value of μ must be used

$$-|\mu|\rho_2 A_{95}\dot{\phi}_2 \qquad \text{(D-771)}$$

Note that A_{95} is an absolute value.

With the above considerations, equation D-765 becomes

$$F_{23F}[a_{G2}(-\cos(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2}) + \mu s_{2F}\sin(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2}))$$

$$+ \mu s_{2F}\rho_{G2} + \mu\rho_2 A_{96FF}\} - F_{12F}[g_1 - \mu\rho_2 A_{97FF}]$$

$$+ \mu[\rho_{f2}A_{98} + \rho_2 A_{94}] - |\mu|\rho_2 A_{95}\dot{\phi}_2 = A_{99} + A_{100}\ddot{\phi}_2 \qquad \text{(D-772)}$$

Finally, the above is solved for F_{23F}

$$F_{23F} = \frac{A_{102FF}F_{12F} - A_{103} + A_{104}\dot{\phi}_2 + A_{99} + A_{100}\ddot{\phi}_2}{A_{101FF}} \tag{D-773}$$

where

$$A_{101FF} = a_{G2}\left(-\cos\left(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}\right) + \mu s_{2F}\sin\left(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}\right)\right)$$

$$+ \mu\left(\rho_2 A_{96FF} + s_{2F}\rho_{G2}\right) \tag{D-774}$$

$$A_{102FF} = g_1 - \mu\rho_2 A_{97FF} \tag{D-775}$$

$$A_{103} = \mu\left[\rho_{f2}A_{98} + \rho_2 A_{94}\right] \tag{D-776}$$

$$A_{104} = |\mu|\,\rho_2 A_{95} \tag{D-777}$$

Dynamics of Gear and Pinion No. 2, with Mesh No. 2 in Round-on-Round Contact and Mesh No. 1 in Round-on-Flat Contact

A schematic top view of a free body diagram of gear and pinion no. 2 with mesh no. 2 in round-on-round contact and mesh no. 2 in round-on-flat contact is represented in figure D-16. It shows the contact force

$$\overline{F}_{32} = -\overline{F}_{23} = -F_{23}\overline{n}_{\lambda 2} \tag{D-778}$$

of pinion no. 3 and gear no. 2, opposite to force $\overline{F}_{23}$ as given by equation D-145a. The associated friction force $\overline{F}_{f32}$ is opposite to $\overline{F}_{f23}$ of eq. D-146. Thus,

$$\overline{F}_{f32} = -\overline{F}_{f23} = \mu s_{2R}F_{23}\overline{n}_{N\lambda 2} \tag{D-779}$$

Further, the contact force $\overline{F}_{12F}$ of gear no. 1 and pinion no. 2 is shown in figure D-16. This force is opposte to $\overline{F}_{21F}$ of equation D-538. Then

$$\overline{F}_{12F} = -\overline{F}_{21F} = -F_{12F}\overline{n}_{NF1} \tag{D-780}$$

The associated friction force $\overline{F}_{f12F}$ is opposite in direction to the friction force $\overline{F}_{f21F}$ of equation D-540, i.e.,

$$\overline{F}_{f12F} = -\overline{F}_{f21F} = \mu s_{1F}F_{12F}\overline{n}_{F1} \tag{D-781}$$

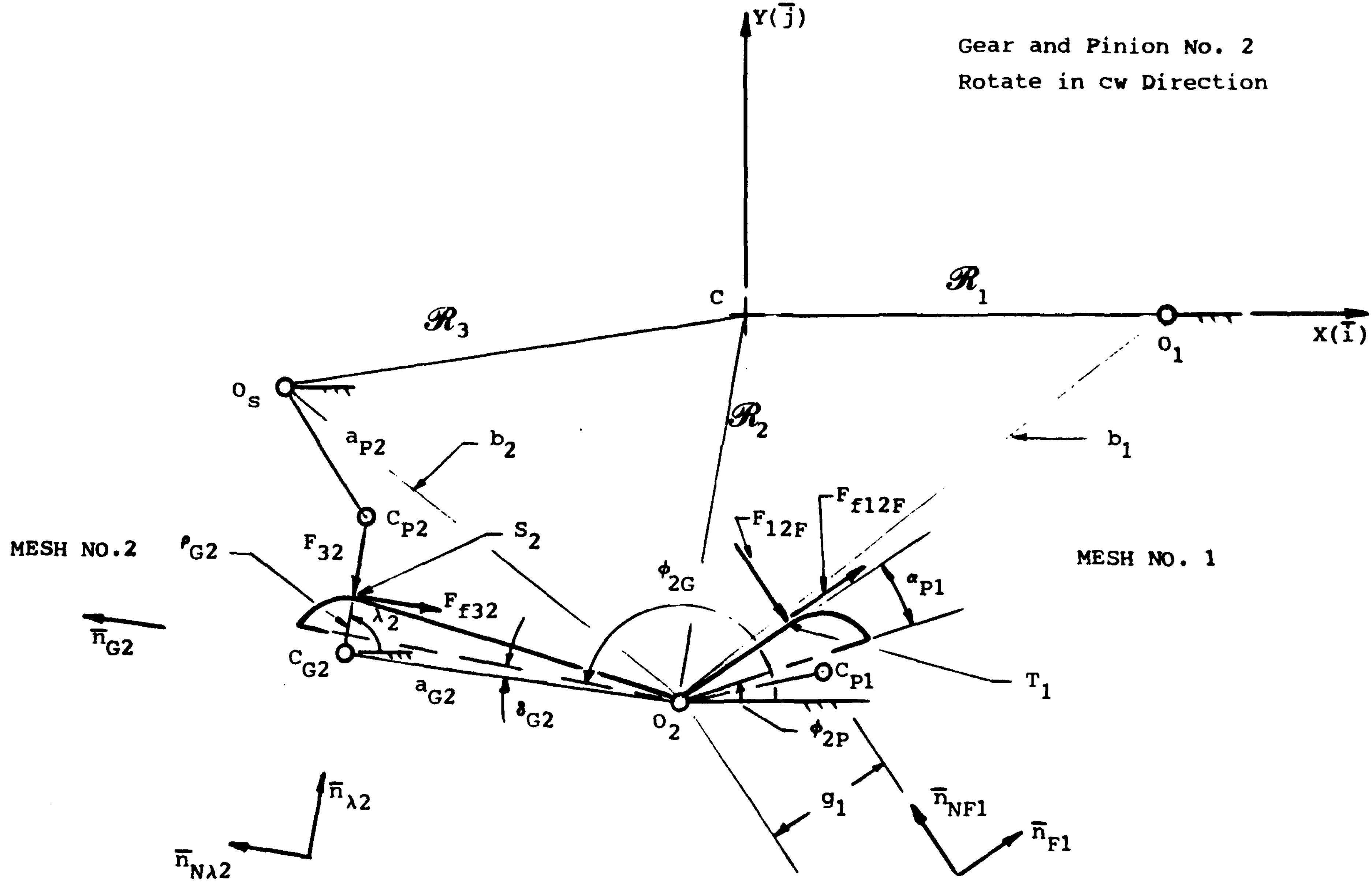


Figure D-16. Top view of free body diagram of gear and pinion no. 2. Mesh no. 2 is in round-on-round contact and mesh no. 1 is in round-on-flat contact

Again, figure D-14b represents the appropriate free body diagram of the pivot shaft of gear and pinion no. 2.

Force Equations

The force equation is again based on Newton's law, i.e.

$$\Sigma\bar{F} = m_2\bar{A}_{O_2/ground} \tag{D-782}$$

where

$\Sigma\bar{F}$ = Sum of the pivot forces as well as the various contact forces

m_2 = Mass of gear and pinion no. 2

$\bar{A}_{O_2/ground}$ = Acceleration of the component center of mass, i.e., equation D-605

The full force equation is now obtained with the help of figures D-16 and D-14b, as well as equations D-778 to D-781

$$-F_{23}\bar{n}_{\lambda 2} - \mu s_{2R}F_{23}\bar{n}_{N\lambda 2} - F_{12F}\bar{n}_{NF1} + \mu s_{1F}F_{12F}\bar{n}_{F1}$$
$$+ F_{x2u}\bar{i} - \mu F_{x2u}\bar{j} + F_{y2u}\bar{j} + \mu F_{y2u}\bar{i} + F_{z2}\bar{k} - F_{x2L}\bar{i} + \mu F_{x2L}\bar{j}$$
$$- F_{y2L}\bar{j} - \mu F_{y2L}\bar{i} = m_2\left(Q_x\bar{i} + Q_y\bar{j} + Q_z\bar{k}\right) \tag{D-783}$$

In the above, $\bar{n}_{\lambda 2}$ and $\bar{n}_{N\lambda 2}$ are given by equations D-145b and D-147, respectively. The unit vectors $\bar{n}_{NF1}$ and $\bar{n}_{F1}$ are defined by equations D-539 and D-541. Appropriate substitution and subsequent separation of components furnishes the following:

<u>X-Component of Force Equations</u>

$$-F_{23}\cos\lambda_2 + \mu s_{2R}F_{23}\sin\lambda_2 + F_{12F}\sin\left(\phi_{2P} + \alpha_{P1}\right)$$
$$+ \mu s_{1F}F_{12F}\cos\left(\phi_{2P} + \alpha_{P1}\right) + F_{x2u} + \mu F_{y2u} - F_{x2L} - \mu F_{y2L} = m_2Q_x \tag{D-784}$$

Y-Component of Force Equation

$$-F_{23}\sin\lambda_2 - \mu s_{2R}F_{23}\cos\lambda_2 - F_{12F}\cos\left(\phi_{2P} + \alpha_{P1}\right) + \mu s_{1F}F_{12F}\sin\left(\phi_{2P} + \alpha_{P1}\right)$$

$$- \mu F_{x2u} + F_{y2u} + \mu F_{x2L} - F_{y2L} = m_2 Q_y \qquad \text{(D-785)}$$

Z-Component of Force Equation

This thrust force is again expressed in tilded form, so that

$$\widetilde{F}_{z2} = |m_2 Q_z| \qquad \text{(D-786)}$$

Moment Equations

The moment equation is again expressed in terms of the projectile-fixed coordinate system by way of equation D-618.

The angular velocity $\dot{\phi}_2$ and the angular acceleration $\ddot{\phi}_2$ must in this case reflect the round-on-round contact of mesh no. 2, when these quantities are expressed in terms of the escape wheel angular velocity and acceleration.

The applicable expression for the moment $\overline{M}_{O_2}$ is now found with the help of the free body diagrams of figures D-16 and D-14b. The remarks concerning the thrust friction torque following equation D-618 still holds. Then

$$\overline{M}_{O_2} = \left(a_{G2}\overline{n}_{G2} + \rho_{G2}\overline{n}_{\lambda 2}\right) \times \left(-F_{23}\overline{n}_{\lambda 2} - \mu s_{2R}F_{23}\overline{n}_{N\lambda 2}\right)$$

$$+ g_1\overline{n}_{F1} \times \left(-F_{12F}\overline{n}_{NF1}\right) + \mu\rho_{f2}\widetilde{F}_{z2}\overline{k} + \left(L_u\overline{k} - \rho_2\overline{i}\right) \times \left(F_{x2u}\overline{i} - \mu F_{x2u}\overline{j}\right)$$

$$+ \left(L_u\overline{k} - \rho_2\overline{j}\right) \times \left(F_{y2u}\overline{j} + \mu F_{y2u}\overline{i}\right) + \left(-L_L\overline{k} + \rho_2\overline{i}\right) \times \left(-F_{x2L}\overline{i} + \mu F_{x2L}\overline{j}\right)$$

$$+ \left(-L_L\overline{k} + \rho_2\overline{j}\right) \times \left(-F_{y2L}\overline{j} - \mu F_{y2L}\overline{i}\right) \qquad \text{(D-787)}$$

The above becomes with equations G-47, G-48, G-49, and G-22 and G-23 of ref 5

$$\overline{M}_{O_2} = \left[\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L}\right]\overline{i}$$

$$+ \left[L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L}\right]\overline{j}$$

$$+ \left[F_{23}\left\{a_{G2}\left(\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R}\cos(\phi_{2G} + \delta_{G2} - \lambda_2)\right) - \mu\rho_{G2}s_{2R}\right\}\right.$$

$$\left. - g_1F_{12F} + \mu\rho_{f2}\widetilde{F}_{z2} + \mu\rho_2\left(F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L}\right)\right]\overline{k} \qquad \text{(D-788)}$$

Substitution of equation D-788 into equation D-618 yields the following moment component expressions

X-Component of Gear and Pinion Moment Equation

$$\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L}$$

$$= I_{x2}\dot{\omega}_x + I_{z2}\omega_y\left(\omega_z + \dot{\phi}_2\right) - I_{y2}\omega_y\omega_z \qquad \text{(D-789)}$$

Y-Component of Gear and Pinion Moment Equation

$$L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L}$$

$$= I_{y2}\dot{\omega}_y + I_{x2}\omega_x\omega_z - I_{z2}\omega_x\left(\omega_z + \dot{\phi}_2\right) \qquad \text{(D-790)}$$

Z-Component of Gear and Pinion Moment Equation

$$F_{23}\left[a_{G2}\left(\sin\left(\phi_{2G} + \delta_{G2} - \lambda_2\right) - \mu s_{2R}\cos\left(\phi_{2G} + \delta_{G2} - \lambda_2\right)\right) - \mu\rho_{G2}s_{2R}\right]$$

$$- g_1 F_{12F} + \mu\rho_{12}\widetilde{F}_{z2} + \mu\rho_2\left(F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L}\right)$$

$$= I_{z2}\left(\dot{\omega}_z + \ddot{\phi}_2\right) \qquad \text{(D-791)}$$

Simplification of Force and Moment Equations and Determination of Pivot Forces on Gear and Pinion No. 2

X-Component of the Force Equation

Equation D-784 is now rewritten

$$-F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} = A_{84RF}F_{23} + A_{85RF}F_{12} + A_{86} \qquad \text{(D-792)}$$

where

$$A_{84RF} = -\cos\lambda_2 + \mu s_{2R}\sin\lambda_2 \qquad \text{(D-793)}$$

$$A_{85RF} = \sin\left(\phi_{2P} + \alpha_{P1}\right) + \mu s_{1F}\cos\left(\phi_{2P} + \alpha_{P1}\right) \qquad \text{(D-794)}$$

$$A_{86} = -m_2 Q_x \qquad \text{(D-795)}$$

Y-Component of the Force Equation

Equation D-785 is rewritten

$$\mu F_{x2u} - F_{y2u} - F_{x2L} + F_{y2L} = A_{87RF}F_{23} + A_{88RF}F_{12F} + A_{89} \tag{D-796}$$

where

$$A_{87RF} = -\left(\sin\lambda_2 + \mu s_{2R}\cos\lambda_2\right) \tag{D-797}$$

$$A_{88RF} = -\cos\left(\phi_{2P} + \alpha_{P1}\right) + \mu s_{1F}\sin\left(\phi_{2P} + \alpha_{P1}\right) \tag{D-798}$$

$$A_{89} = -m_2 Q_y \tag{D-799}$$

Z-Component of the Force Equation

Remains as in equation D-786.

X-Component of the Moment Equation

Equation D-789 is rewritten

$$-\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = A_{90} + A_{91}\dot{\phi}_2 \tag{D-800}$$

where

$$A_{90} = -\left[I_{x2}\dot{\omega}_x + \omega_y\omega_z\left(I_{z2} - I_{y2}\right)\right] \tag{D-801}$$

$$A_{91} = -I_{z2}\omega_y \tag{D-802}$$

Y-Component of the Moment Equation

Equation D-790 is rewritten

$$-L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} = A_{92} + A_{93}\dot{\phi}_2 \tag{D-803}$$

where

$$A_{92} = -\left[I_{y2}\dot{\omega}_y + \omega_x\omega_z\left(I_{x2} - I_{z2}\right)\right] \tag{D-804}$$

$$A_{93} = I_{z2}\omega_x \tag{D-805}$$

Equation D-791 for the Z-component of the moment remains as is.

Simultaneous Solution of Pivot Forces

Equations D-792, D-796, D-800, and D-803 are now solved simultaneously for the pivot forces. Therefore,

$$\left.\begin{array}{l} -F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} = B_{21} \\ \mu F_{x2u} - F_{y2u} - \mu F_{x2L} + F_{y2L} = B_{22} \\ -\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = B_{23} \\ -L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} = B_{24} \end{array}\right\} \quad \text{(D-806)}$$

where

$$B_{21} = A_{84RF}F_{23} + A_{85RF}F_{12F} + A_{86} \quad \text{(D-807)}$$

$$B_{22} = A_{87RF}F_{23} + A_{88RF}F_{12F} + A_{89} \quad \text{(D-808)}$$

$$B_{23} = A_{90} + A_{91}\dot{\phi}_2 \quad \text{(D-809)}$$

$$B_{24} = A_{92} + A_{93}\dot{\phi}_2 \quad \text{(D-810)}$$

Again, as before the B_{2i} do not reflect the mesh contact modes. The A's and C's account for these variations as needed.

To use the solutions of equation D-67, equation D-806 has to be changed to a form that has the same signs as this set of expressions. This may be accomplished by substituting

$$\mu^* = -\mu \quad \text{(D-811)}$$

(This replaces $A_{11} = \mu_1 s_5$ in equation D-67.) Equation D-806 then becomes

$$\left.\begin{array}{l} -F_{x2u} + \mu^* F_{y2u} + F_{x2L} - \mu^* F_{y2L} = B_{21} \\ -\mu^* F_{x2u} - F_{y2u} + \mu^* F_{x2L} + F_{y2L} = B_{22} \\ \mu^* L_u F_{x2u} + L_u F_{y2u} + \mu^* L_L F_{x2L} + L_L F_{y2L} = B_{23} \\ -L_u F_{x2u} + \mu^* L_u F_{y2u} - L_L F_{x2L} + \mu^* L_L F_{y2L} = B_{24} \end{array}\right\} \quad \text{(D-812)}$$

With this substitution (i.e., equation D-811) the coefficient determinant of equation D-812 becomes according to equation D-75

$$D = \left[(L_u + L_L)\left(1 + \mu^2\right) \right]^2 \tag{D-813}$$

According to equation D-80, the determinant $D_{F_{x2u}}$ now becomes with the appropriate changes

$$D_{F_{x2u}} = (L_u + L_L)\left(1 + \mu^2\right)\left[-L_L B_{21} + \mu L_L B_{22} - \mu B_{23} - B_{24}\right] \tag{D-814}$$

Now substitute for the B_{2i}'s according to equations D-807 and D-810

$$\begin{aligned} D_{F_{x2u}} = (L_u + L_L)\left(1 + \mu^2\right)\Big\{ &-L_L \left[A_{84RF}F_{23} + A_{85RF}F_{12F} + A_{86}\right] \\ &+ \mu L_L \left[A_{87RF}F_{23} + A_{88RF}F_{12F} + A_{89}\right] \\ &- \mu\left[A_{90} + A_{91}\dot{\phi}_2\right] - \left[A_{92} + A_{93}\dot{\phi}_2\right] \Big\} \end{aligned} \tag{D-815}$$

After collecting of terms, the tilded force $\widetilde{F}_{x2u}$ becomes

$$\widetilde{F}_{x2u} = \frac{\widetilde{D}_{F_{x2u}}}{D} = \frac{1}{L_T\left(1 + \mu^2\right)}\left[C_{57} + C_{58}\dot{\phi}_2 + C_{58RF}F_{23} + C_{60RF}F_{12F}\right] \tag{D-816}$$

where

$$C_{57} = \left| -L_L A_{86} + \mu\left(L_L A_{89} - A_{90}\right) - A_{92} \right| \tag{D-817}$$

$$C_{58} = \left| \mu A_{91} + A_{93} \right| \tag{D-818}$$

$$C_{59RF} = \left| L_L\left(\mu A_{87RF} - A_{84RF}\right) \right| \tag{D-819}$$

$$C_{60RF} = \left| L_L\left(\mu A_{88RF} - A_{85RF}\right) \right| \tag{D-820}$$

According to equation D-90, $D_{F_{y2u}}$ with appropriate changes becomes

$$D_{F_{y2u}} = (L_u + L_L)\left(1 + \mu^2\right)\left[-\mu L_L B_{21} - L_L B_{22} + B_{23} - \mu B_{24}\right] \tag{D-821}$$

Substitution of equations D-807 to D-810 gives

$$\begin{aligned} D_{F_{y2u}} = (L_u + L_L)\left(1 + \mu^2\right)\Big\{ &-\mu L_L \left[A_{84RF}F_{23} + A_{85RF}F_{12F} + A_{86}\right] \\ &-L_L \left[A_{87RF}F_{23} + A_{88RF}F_{12F} + A_{89}\right] \\ &+ \left[A_{90} + A_{91}\dot{\phi}_2\right] - \mu\left[A_{92} + A_{93}\dot{\phi}_2\right] \Big\} \end{aligned} \tag{D-822}$$

After appropriate collecting of terms, the tilded force $\widetilde{F}_{y2u}$ becomes

$$\widetilde{F}_{y2u} = \frac{\widetilde{D}_{F_{y2u}}}{D} = \frac{1}{L_T\left(1+\mu^2\right)}\left[C_{61} + C_{62}\dot{\phi}_2 + C_{63RF}F_{23} + C_{64RF}F_{12F}\right] \tag{D-823}$$

where

$$C_{61} = \left|-L_L A_{89} - \mu\left(L_L A_{86} + A_{92}\right) + A_{90}\right| \tag{D-824}$$

$$C_{62} = \left|A_{91} - \mu A_{93}\right| \tag{D-825}$$

$$C_{63RF} = \left|L_L\left(\mu A_{84RF} + A_{87RF}\right)\right| \tag{D-826}$$

$$C_{64RF} = \left|L_L\left(\mu A_{85RF} + A_{88RF}\right)\right| \tag{D-827}$$

According to equation D-100, $D_{F_{x2L}}$ with the applicable changes becomes

$$D_{F_{x2L}} = \left(L_u + L_L\right)\left(1+\mu^2\right)\left\{L_u B_{21} - \mu L_u B_{22} - \mu B_{23} - B_{24}\right\} \tag{D-828}$$

Substitute equations D-807 to D-810

$$\begin{aligned} D_{F_{x2L}} = \left(L_u + L_L\right)\left(1+\mu^2\right)\Big\{ & L_u\left[A_{84RF}F_{23} + A_{85RF}F_{12F} + A_{86}\right] \\ & - \mu L_u\left[A_{87RF}F_{23} + A_{88RF}F_{12F} + A_{89}\right] \\ & - \left[A_{90} + A_{91}\dot{\phi}_2\right] - \left[A_{92} + A_{93}\dot{\phi}_2\right] \Big\} \end{aligned} \tag{D-829}$$

After collecting of terms, the tilded force $\widetilde{F}_{x2L}$ becomes

$$\widetilde{F}_{x2L} = \frac{\widetilde{D}_{F_{x2L}}}{D} = \frac{1}{L_T\left(1+\mu^2\right)}\left[C_{65} + C_{66}\dot{\phi}_2 + C_{67RF}F_{23} + C_{68RF}F_{12F}\right] \tag{D-830}$$

where

$$C_{65} = \left|-\mu\left(L_u A_{89} + A_{90}\right) + L_u A_{86} - A_{92}\right| \tag{D-831}$$

$$C_{66} = \left|\mu A_{91} + A_{93}\right| \tag{D-832}$$

$$C_{67RF} = \left|L_u\left(A_{84RF} - \mu A_{87RF}\right)\right| \tag{D-833}$$

$$C_{68RF} = \left|L_u\left(A_{85RF} - \mu A_{88RF}\right)\right| \tag{D-834}$$

According to equation D-109, the determinant $D_{F_{y2L}}$ after applicable adaptation becomes

$$D_{F_{y2L}} = (L_u + L_L)(1 + \mu^2)\{\mu L_u B_{21} + L_u B_{22} + B_{23} - \mu B_{24}\} \qquad \text{(D-835)}$$

Substitution of equations D-807 to D-810 leads to

$$D_{F_{y2L}} = (L_u + L_L)(1 + \mu^2)\{\mu L_u [A_{84RF}F_{23} + A_{85RF}F_{12F} + A_{86}]$$
$$+ L_u [A_{87RF}F_{23} + A_{88RF}F_{12F} + A_{89}]$$
$$+ [A_{90} + A_{91}\dot{\phi}_2] - \mu [A_{92} + A_{93}\dot{\phi}_2]\} \qquad \text{(D-836)}$$

Again, terms are collected and an expression for the tilded force $\widetilde{F}_{y2L}$ is found. Therefore

$$\widetilde{F}_{y2L} = \frac{\widetilde{D}_{F_{y2L}}}{D} = \frac{1}{L_T(1 + \mu^2)}\left[C_{69} + C_{70}\dot{\phi}_2 + C_{71RF}F_{23} + C_{72RF}F_{12F}\right] \qquad \text{(D-837)}$$

where

$$C_{69} = |L_u A_{89} + \mu (L_u A_{86} - A_{92}) + A_{90}| \qquad \text{(D-838)}$$

$$C_{70} = |A_{91} - \mu A_{93}| \qquad \text{(D-839)}$$

$$C_{71RF} = |L_u (\mu A_{84RF} + A_{87RF})| \qquad \text{(D-840)}$$

$$C_{72RF} = |L_u (\mu A_{85RF} + A_{88RF})| \qquad \text{(D-841)}$$

Determination of Contact Force $\overline{F}_{23}$ in Terms of Contact Force $\overline{F}_{12F}$ and Gear and Pinion Parameters. Mesh No. 2 is in Round-on-Round Contact and Mesh No. 1 in Round-on-Flat Contact

Substitution of equations D-786, D-816, D-823, D-830, and D-837 into the Z-moment equation D-791 is now required. First, let the tilded forces be added

$$\widetilde{F}_{x2u} + \widetilde{F}_{y2u} + \widetilde{F}_{x2L} + \widetilde{F}_{y2L} = A_{94} + A_{95}\dot{\phi} + A_{96RF}F_{23} + A_{97RF}F_{12F} \qquad \text{(D-842)}$$

where

$$A_{94} = \frac{C_{57} + C_{61} + C_{65} + C_{69}}{L_T\left(1 + \mu^2\right)} \tag{D-843}$$

$$A_{95} = \frac{C_{58} + C_{62} + C_{66} + C_{70}}{L_T\left(1 + \mu^2\right)} \tag{D-844}$$

$$A_{96RF} = \frac{C_{59RF} + C_{63RF} + C_{67RF} + C_{71RF}}{L_T\left(1 + \mu^2\right)} \tag{D-845}$$

$$A_{97RF} = \frac{C_{60RF} + C_{64RF} + C_{68RF} + C_{72RF}}{L_T\left(1 + \mu^2\right)} \tag{D-846}$$

Further, let equation D-786 be expressed as

$$\widetilde{F}_{z2} = A_{98} = \left|m_2 Q_z\right| \tag{D-847}$$

Equation D-791 then becomes

$$\begin{aligned}
&F_{23}\left[a_{G2}\left(\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R}\cos(\phi_{2G} + \delta_{G2} - \lambda_2)\right) - \mu\rho_{G2} s_{2R}\right] \\
&- g_1 F_{12F} + \mu\rho_{f2} A_{98} + \mu\rho_2\left[A_{94} \pm A_{95}\dot{\phi}_2 + A_{96RF} F_{23} + A_{97RF} F_{12F}\right] \\
&= I_{z2}(\dot{\omega}_z + \ddot{\phi}_2)
\end{aligned} \tag{D-848}$$

or

$$\begin{aligned}
&F_{23}\left[a_{G2}\left(\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R}\cos(\phi_{2G} + \delta_{G2} - \lambda_2)\right) - \mu\rho_{G2} s_{2R} + \mu\rho_2 A_{96RF}\right] \\
&- F_{12F}\left[g_1 - \mu\rho_2 A_{97RF}\right] + \mu\left[\rho_{f2} A_{98} + \rho_2 A_{94}\right] \pm \mu\rho_2 A_{95}\dot{\phi}_2 \\
&= A_{99} + A_{100}\ddot{\phi}_2
\end{aligned} \tag{D-849}$$

where again, as in equation D-682 and D-683

$$A_{99} = I_{z2}\dot{\omega}_z \tag{D-850}$$

$$A_{100} = I_{z2} \tag{D-851}$$

Now consider again the signs of the friction moment terms, recalling that a reversal in the gear train motion will cause a change of the sign of μ in the program. The component rotates normally in a clockwise direction and the following friction moments must be positive.

$$\mu F_{23}\rho_2 A_{96RF} \tag{D-852}$$

$$\mu F_{12}\rho_2 A_{97RF} \tag{D-853}$$

$$\mu[\rho_{f2}A_{98} + \rho_2 A_{94}] \text{ (} A_{94} \text{ and } A_{98} \text{ are absolute values)} \tag{D-854}$$

The moment represented by the term containing $\dot{\phi}_2$ must always act opposite to the direction of rotation of gear and pinion no. 2. Therefore the term must have a negative sign and the absolute value of μ must be used

$$- |\mu|\, \rho_2\, A_{95}\, \dot{\phi}_2 \tag{D-855}$$

Note that A_{95} is an absolute value.

With the above considerations, equation D-849 becomes

$$F_{23}[a_{G2}(\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R}\cos(\phi_{2G} + \delta_{G2} - \lambda_2)) - \mu\rho_{G2}s_{2R} + \mu\rho_2 A_{96RF}]$$

$$- F_{12F}[g_1 - \mu\rho_2 A_{97RF}] + \mu[\rho_{f2}A_{98} + \rho_2 A_{94}] - |\mu|\rho_2 A_{95}\dot{\phi}_2$$

$$= A_{99} + A_{100}\ddot{\phi}_2 \tag{D-856}$$

Finally, the above is solved for F_{23}

$$F_{23} = \frac{A_{102RF}F_{12F} - A_{103} + A_{104}\dot{\phi}_2 + A_{99} + A_{100}\ddot{\phi}_2}{A_{101RF}} \tag{D-857}$$

$$A_{101RF} = a_{G2}(\sin(\phi_{2G} + \delta_{G2} - \lambda_2) - \mu s_{2R}\cos(\phi_{2G} + \delta_{G2} - \lambda_2))$$

$$- \mu(\rho_{G2}s_{2R} - \rho_2 A_{96RF}) \tag{D-858}$$

$$A_{102RF} = g_1 - \mu\rho_2 A_{97RF} \tag{D-859}$$

$$A_{103} = \mu[\rho_{f2}A_{98} + \rho_2 A_{94}] \tag{D-860}$$

$$A_{104} = |\mu|\rho_2 A_{95} \tag{D-861}$$

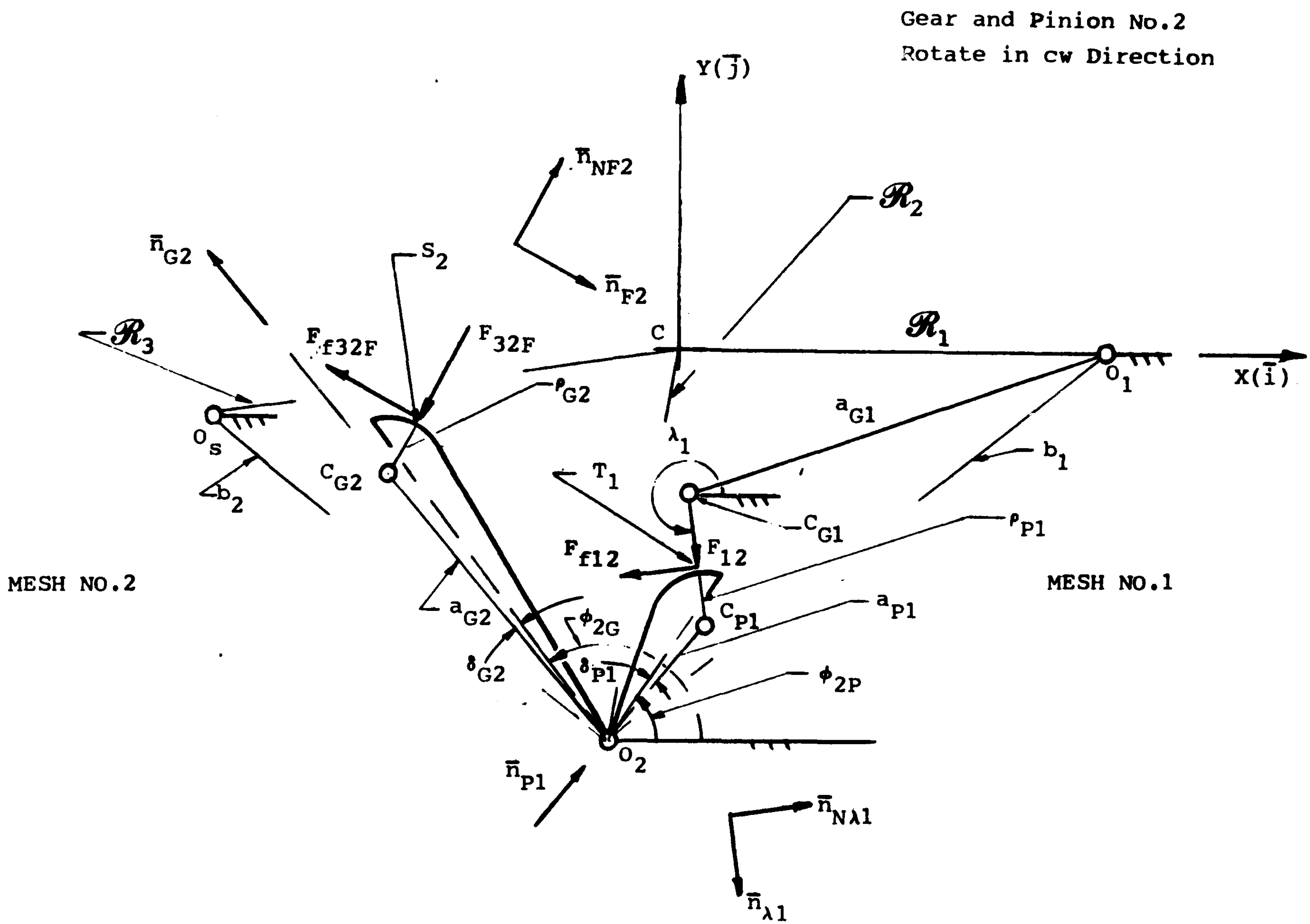


Figure D-17. Top view of free body diagram of gear and pinion no. 2. Mesh no. 2 is in round-on-flat contact and mesh no. 1 is in round-on-round contact

Dynamics of Gear and Pinion No. 2 with Mesh No. 2 in Round-on-Flat Contact and Mesh No. 1 in Round-on-Round Contact

A schematic topview of a free body diagram of gear and pinion no. 2 with mesh no. 2 in round-on-flat contact and mesh no. 1 in round-on-round contact is shown in figure D-17. It shows the contact force

$$\bar{F}_{32F} = -\bar{F}_{23F} = -F_{23F}\bar{n}_{NF2} \quad \text{(D-862)}$$

of pinion no. 3 on gear no. 2, opposite to force $\bar{F}_{23F}$, as given by equation 245a. The associated friction force $\bar{F}_{f32F}$ is opposite to $\bar{F}_{f23F}$, as given by equation D-246. Thus

$$\bar{F}_{f32F} = -\bar{F}_{f23F} = -\mu s_{2F} F_{23F}\bar{n}_{F2} \quad \text{(D-863)}$$

Figure D-17 further shows the contact force $\bar{F}_{12}$ gear no. 1 and pinion no. 2. This force is opposite in direction to contact force $\bar{F}_{21}$, which is given by equation D-426. Thus

$$\bar{F}_{12} = -\bar{F}_{21} = F_{12}\bar{n}_{\lambda 1} \quad \text{(D-864)}$$

The associated friction force $\bar{F}_{f12}$ is opposite in direction to the friction force $\bar{F}_{f21}$ of equation D-428, i.e.

$$\bar{F}_{f12} = -\bar{F}_{f21} - \mu s_{1R} F_{12}\bar{n}_{N\lambda 1} \quad \text{(D-865)}$$

Again, figure D-14b represents the applicable free body diagram for the pivot shaft of gear and pinion no. 2.

Force Equations

The force equation is again based on Newton's law, i.e.

$$\Sigma\bar{F} = m_2\bar{A}_{O2/ground} \quad \text{(D-866)}$$

where

$\Sigma\bar{F}$ = sum of the pivot forces as well as the various contact forces

m_2 = mass of gear and pinion no. 2

$\bar{A}_{O2/ground}$ = acceleration of the component center of mass, i.e., equation D-605

The full force equation is now obtained with the help of figures D-14a and D-14b, as well as equations D-862 to D-865

$$-F_{23F}\bar{n}_{NF2} - \mu s_{2F}F_{23F}\bar{n}_{F2} + F_{12}\bar{n}_{\lambda 1} + \mu s_{1R}F_{12}\bar{n}_{N\lambda 1}$$

$$+ F_{x2u}\bar{i} - \mu F_{x2u}\bar{j} + F_{y2u}\bar{j} + \mu F_{y2u}\bar{i} + F_{z2}\bar{k} - F_{x2L}\bar{i}$$

$$+ \mu F_{x2L}\bar{j} - F_{y2L}\bar{j} - \mu F_{y2L}\bar{i} = m_2\left(Q_x\bar{i} + Q_y\bar{j} + Q_z\bar{k}\right) \tag{D-867}$$

In the above, $\bar{n}_{NF2}$ and $\bar{n}_{F2}$ are given by equations D-245b and D-247, respectively. The unit vectors $\bar{n}_{\lambda 1}$ and $\bar{n}_{N\lambda 1}$ are in turn defined by equations D-427 and D-429.

Appropriate substitution of the above unit vectors into equation D-867 and subsequent separation of components furnishes the following:

X-Component of Force Equation

$$F_{23F}\sin\left(\phi_s - \alpha_{P2}\right) - \mu s_{2F}F_{23F}\cos\left(\phi_s - \alpha_{P2}\right) + F_{12}\cos\lambda_1$$

$$- \mu s_{1R}F_{12}\sin\lambda_1 + F_{x2u} + \mu F_{y2u} - F_{x2L} - \mu F_{y2L} = m_2 Q_x \tag{D-868}$$

Y-Component of Force Equation

$$- F_{23F}\cos\left(\phi_s - \alpha_{P2}\right) - \mu s_{2F}F_{23F}\sin\left(\phi_s - \alpha_{P2}\right) + F_{12}\sin\lambda_1$$

$$+ \mu s_{1R}F_{12}\cos\lambda_1 - \mu F_{x2u} + F_{y2u} + \mu F_{x2L} - F_{y2L} = m_2 Q_y \tag{D-869}$$

Z-Component of Force Equation

This thrust force is again expressed in tilded form, so that

$$\tilde{F}_{z2} = \left| m_2 Q_z \right| \tag{D-870}$$

Moment Equations

The moment equation is again expressed in terms of the projectile-fixed corrdinate system by way of equation D-618.

The angular velocity $\dot{\phi}_2$ and the angular acceleration $\ddot{\phi}_2$ must in this case reflect the round-on-flat contact of mesh no. 2, when these quantities are expressed in terms of the escape wheel angular velocity and acceleration.

The applicable expression for the moment $\overline{M}_{O_2}$ is now found with the help of the free body diagrams of figures D-17 and D-14b. The remarks concerning the thrust friction torque following equation D-618 still holds. Then

$$\overline{M}_{O_2} = (a_{G2}\overline{n}_{G2} + \rho_{G2}\overline{n}_{NF2}) \times (-F_{23F}\overline{n}_{NF2} - \mu s_{2F}F_{23F}\overline{n}_{F2})$$
$$+ (a_{P1}\overline{n}_{P1} - \rho_{P1}\overline{n}_{\lambda 1}) \times (F_{12}\overline{n}_{\lambda 1} + \mu s_{1R}F_{12}\overline{n}_{N\lambda 1})$$
$$+ \mu\rho_{f2}\widetilde{F}_{z2}\overline{k} + (L_u\overline{k} - \rho_2\overline{i}) \times (F_{x2u}\overline{i} - \mu F_{x2u}\overline{j})$$
$$+ (L_u\overline{k} - \rho_2\overline{j}) \times (F_{y2u}\overline{j} + \mu F_{y2u}\overline{i})$$
$$+ (-L_L\overline{k} + \rho_2\overline{i}) \times (-F_{x2L}\overline{i} + \mu F_{x2L}\overline{j})$$
$$+ (-L_L\overline{k} + \rho_2\overline{j}) \times (-F_{y2L}\overline{j} - \mu F_{y2L}\overline{i}) \qquad \text{(D-871)}$$

The above becomes with the help of equations G-2, G-3, G-4, and G-47, G-64, and G-65 of ref 5

$$\overline{M}_{O_2} = [\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L}]\,\overline{i}$$
$$+ [L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L}]\,\overline{j}$$
$$+ [F_{23F}\{a_{G2}(-\cos(\phi_{G2} + \delta_{G2} - \phi_s + \alpha_{P2}) + \mu s_{2F}\sin(\phi_{G2} - \delta_{G2} - \phi_2 + \alpha_{P2}))$$
$$+ \rho_{G2}\mu s_{2F}\} + F_{12}\{a_{P1}(-\sin(\phi_{2P} - \delta_{P1} - \lambda_1) + \mu s_{1R}\cos(\phi_{2P} - \delta_{P1} - \lambda_1))$$
$$- \mu\rho_{P1}s_{1R}\} + \mu\rho_{f2}\widetilde{F}_{z2} + \mu\rho_2(F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L})]\,\overline{k} \qquad \text{(D-872)}$$

Substitution of equation D-872 into equation D-618 yields the following moment components expressions

X-Component of Gear and Pinion Moment Equation

$$\mu L_u F_{x2u} - L_u F_{y2u} + \mu L_L F_{x2L} - L_L F_{y2L} = I_{x2}\dot{\omega}_x + I_{z2}\omega_y(\omega_z + \dot{\phi}_2) - I_{y2}\omega_y\omega_z \qquad \text{(D-873)}$$

Y-Component of Gear and Pinion Moment Equation

$$L_u F_{x2u} + \mu L_u F_{y2u} + L_L F_{x2L} + \mu L_L F_{y2L} = I_{y2}\dot{\omega}_y + I_{x2}\omega_x\omega_z - I_{z2}\omega_x(\omega_z + \dot{\phi}_2) \qquad \text{(D-874)}$$

Z-Component of Gear and Pinion Moment Equation

$$F_{23F}\left\{a_{G2}\left(-\cos\left(\phi_{2G}+\delta_{G2}-\phi_s+\alpha_{P2}\right)+\mu s_{2F}\sin\left(\phi_{2G}+\delta_{G2}-\phi_s+\alpha_{P2}\right)\right)\right.$$

$$\left.+\mu\rho_{G2}s_{2F}\right\}+F_{12}\left\{a_{P1}\left(-\sin\left(\phi_{2P}-\delta_{2P}-\lambda_1\right)+\mu s_{1R}\cos\left(\phi_{2P}-\delta_{P1}-\lambda_1\right)\right)-\mu\rho_{P1}s_{1R}\right\}$$

$$+\mu\rho_{12}\widetilde{F}_{z2}+\mu\rho_2\left(F_{x2u}+F_{y2u}+F_{x2L}+F_{y2L}\right)=I_{z2}\left(\dot{\omega}+\ddot{\phi}_2\right) \qquad \text{(D-875)}$$

Simplification of Force and Moment Equations and Determination of Pivot Forces on Gear and Pinion No. 2

X-Component of the Force Equation

Equation D-868 is now rewritten

$$-F_{x2u}-\mu F_{y2u}+F_{x2L}+\mu F_{y2L}=A_{84FR}F_{23F}+A_{85FR}F_{12}+A_{86} \qquad \text{(D-876)}$$

where

$$A_{84FR}=\sin\left(\phi_s-\alpha_{P2}\right)-\mu s_{2F}\cos\left(\phi_s-\alpha_{P2}\right) \qquad \text{(D-877)}$$

$$A_{85FR}=\cos\lambda_1-\mu s_{1R}\sin\lambda_1 \qquad \text{(D-878)}$$

$$A_{86}=-m_2Q_x \qquad \text{(D-879)}$$

Y-Component of the Force Equation

Equation D-869 is rewritten

$$\mu F_{x2u}-F_{y2u}-F_{x2L}+F_{y2L}=A_{87FR}F_{23F}+A_{88FR}F_{12}+A_{89} \qquad \text{(D-880)}$$

where

$$A_{87FR}=\left(-\cos\left(\phi_s-\alpha_{P2}\right)+\mu s_{2F}\sin\left(\phi_s-\alpha_{P2}\right)\right) \qquad \text{(D-881)}$$

$$A_{88FR}=\sin\lambda_1+\mu s_{1R}\cos\lambda_1 \qquad \text{(D-882)}$$

$$A_{89}=-m_2Q_y \qquad \text{(D-883)}$$

Z-Component of the Force Equation

Remains as in equation D-870.

X-Component of the Moment Equation

Equation D-873 is rewritten

$$-\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = A_{90} + A_{91}\dot{\phi}_2 \qquad \text{(D-884)}$$

where

$$A_{90} = -\left[I_{x2}\dot{\omega}_x + \omega_y\omega_z\left(I_{z2} - I_{y2}\right)\right] \qquad \text{(D-885)}$$

$$A_{91} = -I_{z2}\omega_y \qquad \text{(D-886)}$$

Y-Component of the Moment Equation

Equation D-874 is rewritten

$$-L_u F_{x2u} + \mu L_u F_{y2u} - L_L F_{x2L} + \mu L_L F_{y2L} = A_{92} + A_{93}\dot{\phi}_2 \qquad \text{(D-887)}$$

where

$$A_{92} = \left[I_{y2}\dot{\omega}_y + \omega_x\omega_z\left(I_{x2} - I_{z2}\right)\right] \qquad \text{(D-888)}$$

$$A_{93} = I_{z2}\omega_x \qquad \text{(D-889)}$$

Equation D-875 for the Z-component of the moment remains as is.

Simultaneous Solutions of Pivot Forces

Equations D-876, D-880, D-884, and D-887 are now solved simultaneously for the pivot forces. Therefore

$$\begin{aligned}
&-F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} = B_{21} \\
&\mu F_{x2u} - F_{y2u} - \mu F_{x2L} + F_{y2L} = B_{22} \\
&-\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = B_{23} \\
&-L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} = B_{24}
\end{aligned} \qquad \text{(D-890)}$$

where

$$B_{21} = A_{84FR}F_{23F} + A_{85FR}F_{12} + A_{86} \tag{D-891}$$

$$B_{22} = A_{87FR}F_{23F} + A_{88FR}F_{12} + A_{89} \tag{D-892}$$

$$B_{23} = A_{90} + A_{91}\dot{\phi}_2 \tag{D-893}$$

$$B_{24} = A_{92} + A_{93}\dot{\phi}_2 \tag{D-894}$$

Again, as before the B_{2i} do not reflect the mesh contact modes. The A's and C's account for these variations as needed.

To use the solutions of equation D-67, equation D-890 has to be changed to a form that has the same signs as this set of expressions. This may be accomplished by substituting

$$\mu^* = -\mu \tag{D-895}$$

(This replaces $A_{11} = \mu_1 s_5$ in equation D-67.) Equation D-890 then becomes

$$\left.\begin{aligned} -F_{x2u} + \mu^* F_{y2u} + F_{x2L} - \mu^* F_{y2L} &= B_{21} \\ -\mu^* F_{x2u} - F_{y2u} + \mu^* F_{x2L} + F_{y2L} &= B_{22} \\ \mu^* L_u F_{x2u} + L_u F_{y2u} + \mu^* L_L F_{x2L} + L_L F_{y2L} &= B_{23} \\ -L_u F_{x2u} + \mu^* L_u F_{y2u} - L_L F_{x2L} + \mu^* L_L F_{y2L} &= B_{24} \end{aligned}\right\} \tag{D-896}$$

With the above substitution (i.e., equation D-895) the coefficient determinant of equation D-896 becomes according to equation D-75

$$D = \left[\left(L_u + L_L\right)\left(1 + \mu^2\right)\right]^2 \tag{D-897}$$

According to equation D-80, the determinant $D_{F_{x2u}}$ now becomes with the appropriate changes

$$D_{F_{x2u}} = \left(L_L + L_U\right)\left(1 + \mu^2\right)\left[-L_L B_{21} + \mu L_L B_{22} - \mu B_{23} - B_{24}\right] \tag{D-898}$$

Now substitute for the B_{2i}'s according to equation D-891 to D-894

$$D_{F_{x2u}} = (L_u + L_L)\left(1 + \mu^2\right)\{-L_L\left[A_{84FR}F_{23F} + A_{85FR}F_{12} + A_{86}\right]$$

$$+ \mu L_L\left[A_{87FR}F_{23F} + A_{88FR}F_{12} + A_{89}\right]$$

$$- \mu\left[A_{90} + A_{91}\dot{\phi}_2\right] - \left[A_{92} + A_{93}\dot{\phi}_2\right]\} \qquad \text{(D-899)}$$

After collecting of terms, the tilded force $\widetilde{F}_{x2u}$ becomes

$$\widetilde{F}_{x2u} = \frac{\widetilde{D}_{F_{x2u}}}{D} = \frac{1}{L_T\left(1 + \mu^2\right)}\left[C_{57} + C_{58}\dot{\phi}_2 + C_{59FR}F_{23F} + C_{60FR}F_{12}\right] \qquad \text{(D-900)}$$

where

$$C_{57} = \left|-L_L A_{86} + \mu\left(L_L A_{89} - A_{90}\right) - A_{92}\right| \qquad \text{(D-901)}$$

$$C_{58} = \left|\mu A_{91} + A_{93}\right| \qquad \text{(D-902)}$$

$$C_{59FR} = \left|L_L\left(\mu A_{87FR} - A_{84FR}\right)\right| \qquad \text{(D-903)}$$

$$C_{60FR} = \left|L_L\left(\mu A_{88FR} - A_{85FR}\right)\right| \qquad \text{(D-904)}$$

According to equation D-90, $D_{F_{y2u}}$ with appropriate changes becomes

$$D_{F_{y2u}} = (L_u + L_L)\left(1 + \mu^2\right)\left[-\mu L_L B_{21} - L_L B_{22} + B_{23} - \mu B_{24}\right] \qquad \text{(D-905)}$$

Substitution of equations D-891 to D-894 gives

$$D_{F_{y2u}} = (L_u + L_L)\left(1 + \mu^2\right)\{-\mu L_L\left[A_{84FR}F_{23F} + A_{85FR}F_{12} + A_{86}\right]$$

$$- L_L\left[A_{87FR}F_{23F} + A_{88FR}F_{12} + A_{89}\right]$$

$$+ \left[A_{90} + A_{91}\dot{\phi}_2\right] - \mu\left[A_{92} + A_{93}\dot{\phi}_2\right]\} \qquad \text{(D-906)}$$

After appropriate collecting of terms, the tilded force $\widetilde{F}_{y2u}$ becomes

$$\widetilde{F}_{y2u} = \frac{\widetilde{D}_{F_{y2u}}}{D} = \frac{1}{L_T\left(1 + \mu^2\right)}\left[C_{61} + C_{62}\dot{\phi}_2 + C_{63FR}F_{23F} + C_{64FR}F_{12}\right] \qquad \text{(D-907)}$$

where

$$C_{61} = |-L_L A_{89} - \mu (L_L A_{86} + A_{92}) - A_{90}| \qquad \text{(D-908)}$$

$$C_{62} = |A_{91} - \mu A_{93}| \qquad \text{(D-909)}$$

$$C_{63FR} = |L_L (\mu A_{84FR} + A_{87FR})| \qquad \text{(D-910)}$$

$$C_{64FR} = |L_L (\mu A_{85FR} + A_{88FR})| \qquad \text{(D-911)}$$

According to equation D-100, $D_{F_{x2L}}$ with the applicable changes becomes

$$D_{F_{x2L}} = (L_u + L_L)(1 + \mu^2)\,[L_u B_{21} - \mu L_u B_{22} - \mu B_{23} - B_{24}] \qquad \text{(D-912)}$$

Substitute equations D-891 to D-894

$$D_{F_{x2L}} = (L_u + L_L)(1 + \mu^2)\{L_u [A_{84FR} F_{23F} + A_{85FR} F_{12} + A_{86}]$$

$$- \mu L_u [A_{87FR} F_{23F} + A_{88FR} F_{12} + A_{89}]$$

$$- \mu [A_{90} + A_{91}\dot{\phi}_2] - [A_{92} + A_{93}\dot{\phi}_2]\} \qquad \text{(D-913)}$$

After collecting of terms, the tilded force $\tilde{F}_{x2L}$ becomes

$$\tilde{F}_{x2L} = \frac{\tilde{D}_{F_{x2L}}}{D} = \frac{1}{L_T(1 + \mu^2)}\left[C_{65} + C_{66}\dot{\phi}_2 + C_{67FR} F_{23F} + C_{68FR} F_{12}\right] \qquad \text{(D-914)}$$

where

$$C_{65} = |-\mu (L_u A_{89} + A_{90}) + L_u A_{86} - A_{92}| \qquad \text{(D-915)}$$

$$C_{66} = |\mu A_{91} + A_{93}| \qquad \text{(D-916)}$$

$$C_{67FR} = |L_u (A_{84FR} - \mu A_{87FR})| \qquad \text{(D-917)}$$

$$C_{68FR} = |L_u (A_{85FR} - \mu A_{88FR})| \qquad \text{(D-918)}$$

According to equation D-109, the determinant $D_{F_{y2L}}$ after applicabe adaptation becomes

$$D_{F_{y2L}} = (L_u + L_L)(1 + \mu^2)\,[\mu L_u B_{21} - L_u B_{22} + B_{23} - \mu B_{24}] \qquad \text{(D-919)}$$

Substitution of equations D-891 to D-894 leads to

$$D_{F_{y2L}} = (L_u + L_L)(1 + \mu^2)\{\mu L_L [A_{84FR}F_{23F} + A_{85FR}F_{12} + A_{86}]$$

$$+ L_u [A_{87FR}F_{23F} + A_{88FR}F_{12} + A_{89}]$$

$$+ [A_{90} + A_{91}\dot{\phi}_2] - \mu [A_{92} + A_{93}\dot{\phi}_2]\} \tag{D-920}$$

Again, terms are collected and an expression for the tilded force $\tilde{F}_{y2L}$ is found. Therefore

$$\tilde{F}_{y2L} = \frac{\tilde{D}_{F_{y2L}}}{D} = \frac{1}{L_T(1 + \mu^2)}\left[C_{69} + C_{70}\dot{\phi}_2 + C_{71FR}F_{23F} + C_{72FR}F_{12}\right] \tag{D-921}$$

where

$$C_{69} = |L_u A_{89} + \mu (L_u A_{86} - A_{92}) + A_{90}| \tag{D-922}$$

$$C_{70} = |A_{91} - \mu A_{93}| \tag{D-923}$$

$$C_{71FR} = |L_u (\mu A_{84FR} + A_{87FR})| \tag{D-924}$$

$$C_{72FR} = |L_u (\mu A_{85FR} + A_{88FR})| \tag{D-925}$$

Determination of Contact Force F_{23F} in Terms of Contact Force F_{12} and Gear and Pinion Parameters. Mesh No. 2 is in Round-on-Flat Contact and Mesh No. 1 in Round-on-Round Contact

Subsitution of equations D-870, D-900, D-907, D-914, and D-921 into the Z-moment equation D-875 is now required. First, let the tilded forces be added

$$\tilde{F}_{x2u} + \tilde{F}_{y2u} + \tilde{F}_{x2L} + \tilde{F}_{y2L} = A_{94} + A_{95}\dot{\phi} + A_{96FR}F_{23F} + A_{97FR}F_{12} \tag{D-926}$$

where

$$A_{94} = \frac{C_{57} + C_{61} + C_{65} + C_{69}}{L_T\left(1 + \mu^2\right)} \tag{D-927}$$

$$A_{95} = \frac{C_{58} + C_{62} + C_{66} + C_{70}}{L_T\left(1 + \mu^2\right)} \tag{D-928}$$

$$A_{96FR} = \frac{C_{59FR} + C_{63FR} + C_{67FR} + C_{71FR}}{L_T\left(1 + \mu^2\right)} \tag{D-929}$$

$$A_{97FR} = \frac{C_{60FR} + C_{64FR} + C_{68FR} + C_{72FR}}{L_T\left(1 + \mu^2\right)} \tag{D-930}$$

Further, let equation D-870 be expressed as

$$\widetilde{F}_{z2} = A_{98} = \left| m_2 Q_z \right| \tag{D-931}$$

Equation D-875 then becomes

$$\begin{aligned} &F_{23F}\left\{a_{G2}\left(-\cos\left(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}\right) + \mu s_{2F}\sin\left(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}\right)\right)\right. \\ &\left.+ \mu s_{2F}\rho_{G2}\right\} + F_{12}\left\{a_{P1}\left(-\sin\left(\phi_{2P} - \delta_{P1} - \lambda_1\right) + \mu s_{1R}\cos\left(\phi_{2P} - \delta_{P1} - \lambda_1\right)\right) - \mu s_{1R}\rho_{P1}\right\} \\ &+ \mu\rho_{f2}A_{98} + \mu\rho_2\left[A_{94} \pm A_{95}\dot{\phi}_2 + A_{96FR}F_{23F} + A_{97FR}F_{12}\right] = I_{z2}\left(\dot{\omega} + \ddot{\phi}_2\right) \end{aligned} \tag{D-932}$$

or

$$\begin{aligned} &F_{23F}\left\{a_{G2}\left(-\cos\left(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}\right) + \mu s_{2F}\sin\left(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}\right)\right)\right. \\ &\left.+ \mu s_{2F}\rho_{G2} + \mu\rho_2 A_{96FR}\right\} + F_{12}\left\{a_{P1}\left(-\sin\left(\phi_{2P} - \delta_{P1} - \lambda_1\right) + \mu s_{1R}\cos\left(\phi_{2P} - \delta_{P1} - \lambda_1\right)\right)\right. \\ &\left.- \mu s_{1R}\rho_{P1} + \mu\rho_2 A_{97FR}\right\} + \mu\left(\rho_{f2}A_{98} + \rho_2 A_{94}\right) \pm \mu\rho_2 A_{95}\dot{\phi}_2 = A_{99} + A_{100}\ddot{\phi}_2 \end{aligned} \tag{D-933}$$

where again, as in equations D-682 and D-683

$$A_{99} = I_{z2}\dot{\omega}_z \tag{D-934}$$

$$A_{100} = I_{z2} \tag{D-935}$$

Now consider again the signs of the friction moment terms, recalling that a reversal in the gear train motion will cause a change of the sign of μ in the program. The component rotates normally in a clockwise direction, and the following friction moments must be positive

$$\mu F_{23}\rho_2 A_{96FR} \tag{D-936}$$

$$F_{12}\rho_2 A_{97FR} \tag{D-937}$$

$$\mu\left[\rho_{f2}A_{98} + \rho_2 A_{94}\right] \text{ (}A_{94}\text{ and }A_{98}\text{ are absolute values)} \tag{D-938}$$

The moment represented by the term containing $\dot{\phi}_2$ must always act opposite to the direction of rotation of gear and pinion no. 2. Therefore, the term must have a negative sign and the absolute value of μ must be used

$$-|\mu|\,\rho_2 A_{95}\dot{\phi}_2 \tag{D-939}$$

Note that A_{95} is an absolute value.

With the above considerations, equation D-933 becomes

$$\begin{aligned}
&F_{23F}\left\{a_{G2}\left(-\cos\left(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}\right) + \mu s_{2F}\sin\left(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}\right)\right)\right. \\
&\left.+ \mu\left(s_{2F}\rho_{G2} + \rho_2 A_{95FR}\right)\right\} + F_{12}\left\{a_{P1}\left(-\sin\left(\phi_{2P} - \delta_{2P} - \lambda_1\right)\right.\right. \\
&\left.\left.+ \mu s_{1R}\cos\left(\phi_{2P} - \delta_{P1} - \lambda_1\right) - \mu\left(s_{1R}\rho_{P1} - \rho_2 A_{97FR}\right)\right)\right\} \\
&+ \mu\left[\rho_{f2}A_{98} + \rho_2 A_{94}\right] - |\mu|\,\rho_2 A_{95}\dot{\phi}_2 = A_{99} + A_{100}\ddot{\phi}_2
\end{aligned} \tag{D-940}$$

Finally, the above is solved for F_{23F}

$$F_{23F} = \frac{A_{102FR}F_{12} - A_{103} + A_{104}\dot{\phi}_2 + A_{99} + A_{100}\ddot{\phi}_2}{A_{101FR}} \tag{D-941}$$

where

$$A_{101FR} = a_{G2}(-\cos(\phi_{2G} + \delta_{G2} - \phi_S + \alpha_{P2}) + \mu s_{2F}\sin(\phi_{2G} + \delta_{G2} - \phi_s + \alpha_{P2}))$$

$$+ \mu(s_{2F}\rho_{G2} + \rho_2 A_{96FR}) \tag{D-942}$$

$$A_{102FR} = a_{P1}(\sin(\phi_{2P} - \delta_{P1} - \lambda_1) - \mu s_{1R}\cos(\phi_{2P} - \delta_{P1} - \lambda_1))$$

$$+ \mu(s_{iR}\rho_{P1} - \rho_2 A_{97FR}) \tag{D-943}$$

$$A_{103} = \mu(\rho_{f2}A_{98} + \rho_2 A_{94}) \tag{D-944}$$

$$A_{104} = |\mu|\rho_2 A_{95} \tag{D-945}$$

DYNAMICS OF COMBINED SYSTEM IN COUPLED MOTION WITH MESHES 1 AND 2 IN ROUND-ON-ROUND CONTACT (RR)

(Applicable to both configurations and entrance and exit conditions)

To develop a single differential equation for the total system in coupled motion and RR contact, equation D-537 for F_{12} is first substituted into equation D-689 for F_{23}

$$F_{23}A_{101RR} = \frac{A_{102RR}}{A_{79R}}[I_{1R}\ddot{\phi}_1 + A_{81}\dot{\phi}_1 + A_{80} + A_{60} + A_{82}\dot{\phi}_1^2$$

$$- m_1 r_{c1}(O_x\sin\gamma - O_y\cos\gamma)]$$

$$- A_{103} + A_{104}\dot{\phi}_2 + A_{99} + A_{100}\ddot{\phi}_2 \tag{D-946a}$$

Equations F-117 and F-122 of appendix F are now used to substitute for $\dot{\phi}_2$ and $\ddot{\phi}_2$ respectively. Similarly, equations F-151 and F-152 serve for $\dot{\phi}_1$ and $\ddot{\phi}_1$. Thus

$$F_{23} = \frac{1}{A_{101RR}}\left\{\frac{A_{102RR}}{A_{79R}}\left[I_{1R}[\ddot{\phi}Y_1Y_5 + \dot{\phi}^2[Y_1Y_6 + Y_2(DER2R)^2]]\right.\right.$$

$$+ A_{81}\dot{\phi}(DER1R)(DER2R) + A_{80} + A_{60} + A_{82}\dot{\phi}^2(DER1R)^2(DER2R)^2$$

$$\left.- m_1 r_{c1}(O_x\sin\gamma - O_y\cos\gamma)\right]$$

$$\left.- A_{103} + A_{104}\dot{\phi}DER2R + A_{99} + A_{100}[\ddot{\phi}Y_5 + \dot{\phi}^2Y_6]\right\} \tag{D-946b}$$

The above expression for F_{23} is now substituted into equation D-372, the combined escapement coupled motion equation with mesh no. 2 in round-on-round contact

$$[A_{51} I_{PR} U - A_{29} I_{zs}] \ddot{\phi} + [A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48}] \dot{\phi}^2 + A_{51} A_{31} U \dot{\phi}$$

$$= A_{29} A_{50} - A_{51}(A_9 + A_{30}) + A_{51} m_p r_{cp}(K_x \sin\beta - K_y \cos\beta)$$

$$+ \frac{A_{29} A_{49R}}{A_{101RR}} \left\{ \frac{A_{102RR}}{A_{79R}} \Big[I_{1R} [\ddot{\phi} Y_1 Y_5 + \dot{\phi}^2 [Y_1 Y_6 + Y_2 (DER2R)^2]] \right.$$

$$+ A_{81} \dot{\phi} (DER1R)(DER2R) + A_{80} + A_{60} + A_{82} \dot{\phi}^2 (DER1R)^2 (DER2R)^2$$

$$- m_1 r_{c1} (O_x \sin\gamma - O_y \cos\gamma) \Big] - A_{103} + A_{104} \dot{\phi} DER2R$$

$$\left. + A_{99} + A_{100} [\ddot{\phi} Y_5 + \dot{\phi}^2 Y_6] \right\} \qquad \text{(D-947)}$$

Collecting of terms leads to

$$\ddot{\phi} \left[A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{100} A_{29} A_{49R} Y_5}{A_{101RR}} - \frac{A_{29} A_{49R} A_{102RR} Y_1 Y_5 I_{1R}}{A_{101RR} A_{79R}} \right]$$

$$+ \dot{\phi}^2 \left[A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48} - \frac{A_{29} A_{49R} A_{102RR}}{A_{101RR} A_{79R}} I_{1R} [Y_1 Y_6 + Y_2 (DER2R)^2] \right.$$

$$\left. - \frac{A_{29} A_{49R} A_{102RR} A_{82}}{A_{101RR} A_{79R}} (DER1R)^2 (DER2R)^2 - \frac{A_{29} A_{49R} A_{100}}{A_{101RR}} Y_6 \right]$$

$$+ \dot{\phi} \left[A_{51} A_{31} U - \frac{A_{29} A_{49R} A_{102RR} A_{81}}{A_{101RR} A_{79R}} (DER1R)(DER2R) - \frac{A_{29} A_{49R} A_{104}}{A_{101RR}} DER2R \right]$$

$$= A_{29} A_{50} - A_{51}(A_9 + A_{30}) + A_{51} m_p r_{cp}(K_x \sin\beta - K_y \cos\beta)$$

$$+ \frac{A_{29} A_{49R}}{A_{101RR}} \left\{ \frac{A_{102RR}}{A_{79R}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin\gamma - O_y \cos\gamma)] - A_{103} + A_{99} \right\} \qquad \text{(D-948)}$$

Finally, the above may be rewritten as[4]

$$A_{105}\ddot{\phi} + A_{106}\dot{\phi}^2 + A_{107}\dot{\phi} = A_{108} + A_{109}(O_x \sin\gamma - O_y \cos\gamma)$$

$$+ A_{110}(K_x \sin\beta - K_y \cos\beta) \tag{D-949}$$

where

$$A_{105} = A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{29} A_{49R} A_{100}}{A_{101RR}} Y_5$$

$$- \frac{A_{29} A_{49R} A_{102RR}}{A_{79R} A_{101RR}} I_{1R} Y_1 Y_5 \tag{D-950}$$

$$A_{106} = A_{51}(A_{32} U^2 + I_{PR} V) - A_{29} A_{48} - \frac{A_{29} A_{49R} A_{102RR}}{A_{79R} A_{101RR}} I_{1R}$$

$$\times [Y_1 Y_6 + Y_2 (DER2R)^2] - \frac{A_{29} A_{49R} A_{82} A_{102RR}}{A_{79R} A_{101RR}} (DER1R)^2 (DER2R)^2$$

$$- \frac{A_{29} A_{49R} A_{100}}{A_{101RR}} Y_6 \tag{D-951}$$

$$A_{107} = A_{51} A_{31} U - \frac{A_{29} A_{49R} A_{81} A_{102RR}}{A_{79R} A_{101RR}} (DER1R)(DER2R)$$

$$- \frac{A_{29} A_{49R} A_{104}}{A_{101RR}} DER2R \tag{D-952}$$

$$A_{108} = A_{29} A_{50} - A_{51}(A_9 + A_{30})$$

$$+ \frac{A_{29} A_{49R}}{A_{101RR}} \left\{ \frac{A_{102RR}}{A_{79R}} [A_{80} + A_{60}] - A_{103} + A_{99} \right\} \tag{D-953}$$

$$A_{109} = - \frac{A_{29} A_{49R} A_{102RR}}{A_{79R} A_{101RR}} m_1 r_{c1} \tag{D-954}$$

$$A_{110} = A_{51} m_p r_{cp} \tag{D-955}$$

[4]The value of the signum function s_7, together with α_{en} or α_{EX}, decides whether entrance or exit-coupled motion is described by the differential equation D-949.

Contact Forces

The contact force F_{23RR} is given by equation D-946b [note new subscript for computational purposes]

$$F_{23RR} = \frac{A_{111}\ddot{\phi} + A_{112}\dot{\phi}^2 + A_{113}\dot{\phi} + A_{114}}{A_{101RR}} \tag{D-956}$$

where

$$A_{111} = \frac{A_{102RR}}{A_{79R}} I_{1R} Y_1 Y_5 + A_{100} Y_5 \tag{D-957}$$

$$A_{112} = \frac{A_{102RR}}{A_{79R}}\Big[I_{1R}(Y_1 Y_6 + Y_2 (DER2R)^2)$$

$$+ A_{82}(DER1R)^2 (DER2R)^2 \Big] + A_{100} Y_6 \tag{D-958}$$

$$A_{113} = \frac{A_{102RR}}{A_{79R}} A_{81}(DER1R)(DER2R) + A_{104}(DER2R) \tag{D-959}$$

$$A_{114} = \frac{A_{102RR}}{A_{79R}} [A_{80} + A_{60} - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma)] - A_{103} + A_{99} \tag{D-960}$$

The contact force F_{12RR} is found with the help of equations D-537, F-142, and F-143

$$F_{12RR} = \frac{1}{A_{79R}}\Big\{ I_{1R}\big[\ddot{\phi}(Y_1 Y_5) + \dot{\phi}^2 (Y_1 Y_6 + Y_2 (DER2R)^2)\big]$$

$$+ A_{81}\dot{\phi}(DER1R)(DER2R) + A_{82}\dot{\phi}^2 ((DER1R)^2 (DER2R)^2$$

$$+ A_{80} + A_{60} - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma) \Big\} \tag{D-961}$$

or

$$F_{12RR} = \frac{A_{115}\ddot{\phi} + A_{116}\dot{\phi}^2 + A_{117}\dot{\phi} + A_{118}}{A_{79R}} \tag{D-962}$$

where

$$A_{115} = I_{1R} Y_1 Y_5 \tag{D-963}$$

$$A_{116} = I_{1R} [Y_1 Y_6 + Y_2 (DER2R)^2 + A_{82}(DER1R)^2 (DER2R)^2 \tag{D-964}$$

$$A_{117} = A_{81}(DER1R)(DER2R) \tag{D-965}$$

$$A_{118} = A_{80} + A_{60} - m_1 r_{c1} (O_x \sin\gamma - O_y \cos\gamma) \tag{D-966}$$

The contact force P_n, between the verge and the escape wheel, may either be obtained in terms of the pallet variable ψ or the escape wheel variable ϕ.

According to equation D-137 or equation D-339, one obtains in terms of $\psi(t)$, using the appropriate value of A_{29} (eq D-400)

$$P_n = \frac{I_{PR}\ddot{\psi} + A_{31}\dot{\psi} + A_{32}\dot{\psi}^2 + A_{119} - m_p r_{cp}(K_x \sin\beta - K_y \cos\beta)}{A_{29}} \tag{D-967}$$

where

$$A_{119} = A_9 + A_{30} \tag{D-968}$$

[see ref 2 for $\ddot{\psi}$ and $\dot{\psi}$ in terms of $\ddot{\phi}$ and $\dot{\phi}$]

When the appropriate value for $A_{51} = A_{51R} = AA_{51R}$ (eq D-371b) is subsituted into equation D-239 or D-364, together with $F_{23} = F_{23RR}$, according to equation D-956, one obtains P_n in terms of $\phi(t)$

$$P_n = \frac{I_{zs}\ddot{\phi} + A_{48}\dot{\phi}^2 + F_{23RR}A_{49R} + A_{50}}{A_{51}} \tag{D-969}$$

NOTE: It must be kept in mind that the $\ddot{\phi}$ and $\dot{\phi}$ terms for all the above contact forces must be those associated with the differential equation D-949.

DYNAMICS OF COMBINED SYSTEM IN COUPLED MOTION WITH MESHES NO. 1 AND NO. 2 IN ROUND-ON-FLAT CONTACT (FF)

Combined Differential Equation

To obtain a single differential equation for the total system in coupled motion and FF contact, equation D-593 for F_{12F} is first substituted into equation D-773 for F_{23F}

$$F_{23F} A_{101FF} = \frac{A_{102FF}}{A_{79F}}\Big[I_{1R}\ddot{\phi}_1 + A_{81}\dot{\phi}_1 + A_{82}\dot{\phi}_1^2 + A_{80}$$

$$+ A_{60} - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma)\Big]$$

$$- A_{103} + A_{104}\dot{\phi}_2 + A_{99} + A_{100}\ddot{\phi} \qquad \text{(D-970)}$$

Equations F-126 and F-131 of appendix F are now substituted for $\dot{\phi}_2$ and $\ddot{\phi}_2$, respectively. Similarly, equations F-150 and F-151 serve for $\dot{\phi}_1$ and $\ddot{\phi}_1$, in turn. Then

$$F_{23F} = \frac{1}{A_{101FF}}\Bigg\{ \frac{A_{102FF}}{A_{79F}}\Big[I_{1R}[\ddot{\phi} Y_3 Y_7 + \dot{\phi}^2 [Y_3 Y_8 + Y_4 (DER2F)^2]]$$

$$+ A_{81}\dot{\phi}(DER1F)(DER2F) + A_{82}\dot{\phi}^2 (DER1F)^2 (DER2F)^2$$

$$+ A_{80} + A_{60} - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma)\Big]$$

$$- A_{103} + A_{104}\dot{\phi} DER2F + A_{99} + A_{100}[\ddot{\phi} Y_7 + \dot{\phi}^2 Y_8]\Bigg\} \qquad \text{(D-971)}$$

The above expression for F_{23F} is now substituted into equation D-403, the combined escapement coupled motion equation, with mesh no. 2 in round-on-flat contact

$$[A_{51} I_{PR} U - A_{29} I_{zs}]\ddot{\phi} + [A_{51}(A_{32} U^2 + I_{PR} V) - A_{29} A_{48}]\dot{\phi}^2 + A_{51} A_{31} U\dot{\phi}$$

$$= A_{29}A_{50} - A_{51}(A_9 + A_{30}) + A_{51} m_p r_{cp}(K_x \sin\beta - K_y \cos\beta)$$

$$+ \frac{A_{29} A_{49F}}{A_{101FF}} \left\{ \frac{A_{102FF}}{A_{79F}} \left[I_{1R} [\ddot{\phi} Y_3 Y_7 + \dot{\phi}^2 (Y_3 Y_8 + Y_4 (DER2F)^2)] \right. \right.$$

$$+ A_{81}\dot{\phi}(DER1F)(DER2F) + A_{82}\dot{\phi}^2(DER1F)^2(DER2F)^2 + A_{80} + A_{60}$$

$$\left. - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma) \right] - A_{103} + A_{104}\dot{\phi} DER2F$$

$$\left. + A_{99} + A_{100}[\ddot{\phi} Y_7 + \dot{\phi}^2 Y_8] \right\} \tag{D-972}$$

Now, the coefficients of like terms are collected

$$\ddot{\phi}\left[A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{100} A_{29} A_{49F}}{A_{101FF}} Y_7 - \frac{A_{29} A_{49F} A_{102FF}}{A_{101FF} A_{79F}} I_{1R} Y_3 Y_7 \right]$$

$$+ \dot{\phi}^2 \left[A_{51}(A_{32}U^2 + I_{PR}V) - A_{29}A_{48} - \frac{A_{82}A_{29}A_{49}A_{102FF}}{A_{101FF}A_{79F}} (DER1F)^2 (DER2F)^2 \right.$$

$$\left. - \frac{A_{100} A_{29} A_{49F}}{A_{101FF}} Y_8 - \frac{A_{29} A_{49F} A_{102FF} I_{1R}}{A_{101FF} A_{79F}} [Y_3 Y_8 + Y_4 (DER2F)^2] \right]$$

$$+ \dot{\phi}\left[A_{51} A_{31} U - \frac{A_{81} A_{29} A_{49F} A_{102FF}}{A_{101FF} A_{79F}} (DER1F)(DER2F) - \frac{A_{104} A_{29} A_{49F}}{A_{101FF}} DER2F \right]$$

$$= A_{29}A_{50} - A_{51}(A_9 + A_{30}) + A_{51}\, m_p r_{cp}(K_x \sin\beta - K_y \cos\beta) + \frac{A_{29} A_{49F}}{A_{101FF}}$$

$$\left\{ \frac{A_{102FF}}{A_{79F}} [A_{80} + A_{60} - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma)] - A_{103} + A_{99} \right\} \tag{D-973}$$

The above may now be rewritten as[5]

$$A_{120}\ddot{\phi} + A_{121}\dot{\phi}^2 + A_{122}\dot{\phi}$$

$$= A_{123} + A_{124}(O_x \sin\gamma - O_y \cos\gamma) + A_{125}(K_x \sin\beta - K_y \cos\beta) \qquad \text{(D-974)}$$

where

$$A_{120} = A_{51} I_{Pr} U - A_{29} I_{zs} - \frac{A_{100} A_{29} A_{49F}}{A_{101FF}} Y_7$$

$$- \frac{A_{29} A_{49F} A_{102FF}}{A_{101FF} A_{79F}} I_{1R} Y_3 Y_7 \qquad \text{(D-975)}$$

$$A_{121} = A_{51}\left(A_{32}U^2 + I_{PR}V\right) - A_{29}A_{48}$$

$$- \frac{A_{82}A_{29}A_{49F}A_{102FF}}{A_{101FF}A_{79F}}(DER1F)^2(DER2F)^2 - \frac{A_{100}A_{29}A_{49F}}{A_{101FF}}Y_8$$

$$- \frac{A_{29}A_{49F}A_{102FF}}{A_{101FF}A_{79F}} I_{1R}\left[Y_3Y_8 + Y_4(DER2F)^2\right] \qquad \text{(D-976)}$$

$$A_{122} = A_{51}A_{31}U - \frac{A_{81}A_{29}A_{49F}A_{102FF}}{A_{101FF}A_{79F}}(DER1F)(DER2F)$$

$$- \frac{A_{104}A_{29}A_{49F}}{A_{101FF}} DER2F \qquad \text{(D-977)}$$

$$A_{123} = A_{29}A_{50} - A_{51}(A_9 + A_{30})$$

$$+ \frac{A_{29}A_{49F}}{A_{101FF}}\left\{\frac{A_{102FF}}{A_{79F}}(A_{80} + A_{60}) - A_{103} + A_{99}\right\} \qquad \text{(D-978)}$$

$$A_{124} = - \frac{A_{29}A_{49F}A_{102FF}}{A_{101FF}A_{79F}} m_1 r_{c1} \qquad \text{(D-979)}$$

$$A_{125} = A_{51} m_P r_{cp} \qquad \text{(D-980)}$$

[5]As in equation D-949, the signum function s_7, as well as the appropriate choice of the angle α, determine whether entrance or exit coupled motion is described.

Contact Forces

The contact force F_{23FF} is given by equation D-971 (note new subscript)

$$F_{23FF} = \frac{A_{126}\ddot{\phi} + A_{127}\dot{\phi}^2 + A_{128}\dot{\phi} + A_{129}}{A_{101FF}} \tag{D-981}$$

where

$$A_{126} = \frac{A_{102FF} I_{1R} Y_3 Y_7}{A_{79F}} + A_{100} Y_7 \tag{D-982}$$

$$A_{127} = \frac{A_{102FF}}{A_{79F}} \Big[I_{1R} [Y_3 Y_8 + Y_4 (DER2F)^2]$$

$$+ A_{82} (DER1F)^2 (DER2F)^2 \Big] + A_{100} Y_8 \tag{D-983}$$

$$A_{128} = \frac{A_{102FF} A_{81}}{A_{79F}} (DER1F)(DER2F) + A_{104} DER2F \tag{D-984}$$

$$A_{129} = \frac{A_{102FF}}{A_{79F}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin\gamma - O_y \cos\gamma)]$$

$$- A_{103} + A_{99} \tag{D-985}$$

The contact force F_{12FF} is found with the help of equations D-593, F-150, and F-151

$$F_{12FF} = \frac{1}{A_{79F}} \Big\{ I_{1R} [\ddot{\phi}(Y_3 Y_7) + \dot{\phi}^2 (Y_3 Y_8 + Y_4 (DER2F)^2)]$$

$$+ A_{81} \dot{\phi}(DER1F)(DER2F) + A_{82} \dot{\phi}^2 (DER1F)^2 (DER2F)^2$$

$$+ A_{80} + A_{60} - m_1 r_{c1} (O_x \sin\gamma - O_y \cos\gamma) \Big] \Big\} \tag{D-986}$$

or

$$F_{12FF} = \frac{A_{130}\ddot{\phi} + A_{131}\dot{\phi}^2 + A_{132}\dot{\phi} + A_{133}}{A_{79F}} \tag{D-987}$$

where

$$A_{130} = I_{1R}Y_3Y_7 \tag{D-988}$$

$$A_{131} = I_{1R}[Y_3Y_8 + Y_4(DER2F)^2] + A_{82}(DER1F)^2(DER2F)^2 \tag{D-989}$$

$$A_{132} = A_{81}(DER1F)(DER2F) \tag{D-990}$$

$$A_{133} = A_{80} + A_{60} - m_1r_{c1}(O_x\sin\gamma - O_y\cos\gamma) \tag{D-991}$$

The contact force P_n, between the verge and the escape wheel, may again be found in terms of $\psi(t)$ with the help of equation D-967. If it is desired to obtain P_n in terms of $\phi(t)$, as applicable to the FF contact mode, equation D-981 for F_{23FF} is substituted into equation D-322 or D-395, keeping in mind that the term $A_{51} = A_{51F} = AA_{51F}$ must contain the appropriate values s_7. Then

$$P_n = \frac{I_{zs}\ddot{\phi} + A_{48}\dot{\phi}^2 + F_{23RR}A_{49R} + A_{50}}{A_{51}} \tag{D-992}$$

For the contact forces F_{23FF}, F_{12FF} and P_n (above), the values of $\ddot{\phi}$ and $\dot{\phi}$ must be those associated with the differential equation D-974, which deals with the FF contact mode.

DYNAMICS OF COMBINED SYSTEM IN COUPLED MOTION WITH MESH NO. 2 IN ROUND-ON-ROUND CONTACT AND MESH NO.1 IN ROUND-ON-FLAT CONTACT (RF)

Combined Differential Equations

To obtain a single differential equation for the total system in coupled motion and RF contact, equation D-593 for F_{12F} is first substituted into equation D-857 for F_{23}

$$\begin{aligned} F_{23}A_{101RF} = \frac{A_{102RF}}{A_{79F}}[I_{1R}\ddot{\phi}_1 + A_{81}\dot{\phi}_1 + + A_{82}\dot{\phi}_1^2 + A_{80} + A_{60} \\ - m_1r_{c1}(O_x\sin\gamma - O_y\cos\gamma)] \\ - A_{103} + A_{104}\dot{\phi}_2 + A_{99} + A_{100}\ddot{\phi}_2 \end{aligned} \tag{D-993}$$

Equations F-108 and F-113 of appendix F are now substituted for $\dot{\phi}_2$ and $\ddot{\phi}_2$, respectively. Similarly, equations F-146 and F-147 serve for $\dot{\phi}_1$ and $\ddot{\phi}_1$.

$$F_{23} = \frac{1}{A_{101RF}}\left\{\frac{A_{102RF}}{A_{79F}}\left[I_{1R}[\ddot{\phi}Y_3Y_5 + \dot{\phi}^2(Y_3Y_6 + Y_4(DER2R)^2)]\right.\right.$$

$$+ A_{81}\dot{\phi}(DER2R)(DER1F) + A_{82}\dot{\phi}^2(DER2R)^2(DER1F)^2$$

$$\left. A_{80} + A_{60} - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma)\right]$$

$$\left. - A_{103} + A_{104}\dot{\phi}DER2R + A_{99} + A_{100}[\ddot{\phi}Y_5 + \dot{\phi}^2 Y_6]\right\} \qquad \text{(D-994)}$$

The above expression for F_{23} is now substituted into equation D-372, the combined escapement coupled motion equation with mesh no. 2 in round-on-round contact

$$[A_{51}I_{PR}U - A_{29}I_{zs}]\ddot{\phi} + [A_{51}(A_{32}U^2 + I_{PR}V) - A_{29}A_{48}]\dot{\phi}^2 + A_{51}A_{31}U\dot{\phi}$$

$$= A_{29}A_{50} - A_{51}(A_9 + A_{30}) + A_{51}m_Pr_{cp}(K_x\sin\beta - K_y\cos\beta)$$

$$+ \frac{A_{29}A_{49R}}{A_{101RF}}\left\{\frac{A_{102RF}}{A_{79F}}\left[I_{1R}[\ddot{\phi}Y_3Y_5 + \dot{\phi}^2(Y_3Y_6 + Y_4(DER2R)^2)]\right.\right.$$

$$+ A_{81}\dot{\phi}(DER2R)(DER1F) + A_{82}\dot{\phi}^2(DER2R)^2(DER1F)^2 + A_{80} + A_{60}$$

$$\left. - m_1 r_{c1}(O_x\sin\gamma - O_y\cos\gamma)\right] - A_{103} + A_{104}\dot{\phi}DER2R$$

$$\left. + A_{99} + A_{100}[\ddot{\phi}Y_5 + \dot{\phi}^2Y_6]\right\} \qquad \text{(D-995)}$$

Now the coefficients of like terms are collected

$$\ddot{\phi}\left[A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{29} A_{49R} A_{102RF}}{A_{79F} A_{101RF}} I_{1R} Y_3 Y_5 - \frac{A_{29} A_{49R} A_{100}}{A_{101RF}} Y_5\right]$$

$$+ \dot{\phi}^2\left[A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48} - \frac{A_{29} A_{49R} A_{102RF}}{A_{79F} A_{101RF}} I_{1R} (Y_3 Y_6 + Y_4 (DER2R)^2)\right.$$

$$\left. - \frac{A_{29} A_{49R} A_{82} A_{102RF}}{A_{101RF} A_{79F}} (DER2R)^2 (DER1F)^2 - \frac{A_{29} A_{49R} A_{100}}{A_{101RF}} Y_6\right]$$

$$+ \dot{\phi}\left[A_{51} A_{31} U - \frac{A_{29} A_{49R} A_{81} A_{102RF}}{A_{79F} A_{101RF}} (DER2R)(DER1F) - \frac{A_{29} A_{49R} A_{104}}{A_{101RF}} DER2R\right]$$

$$= A_{29}A_{50} - A_{51}(A_9 + A_{30}) + A_{51}m_p r_{cp}(K_x \sin\beta - K_y \cos\beta)$$

$$+ \frac{A_{29} A_{49R}}{A_{101RF}}\left\{\frac{A_{102RF}}{A_{79F}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin\gamma - O_y \cos\gamma)] - A_{103} + A_{99}\right\} \quad \text{(D-996)}$$

The above is now rewritten as[6]

$$A_{134} \ddot{\phi} + A_{135} \dot{\phi}^2 + A_{136} \dot{\phi} = A_{137} + A_{138} (O_x \sin\gamma - O_y \cos\gamma)$$

$$+ A_{139} (K_x \sin\beta - K_y \cos\beta) \quad \text{(D-997)}$$

where

$$A_{134} = A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{29} A_{49R} A_{102RF}}{A_{79F} A_{101RF}} I_{1R} Y_3 Y_5$$

$$- \frac{A_{29} A_{49R} A_{100}}{A_{101RF}} Y_5 \quad \text{(D-998)}$$

$$A_{135} = A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48}$$

$$- \frac{A_{29} A_{49} A_{102RF}}{A_{79F} A_{101RF}} I_{1R} (Y_3 Y_6 + Y_4 (DER2R)^2)$$

$$- \frac{A_{29} A_{49R} A_{82} A_{102RF}}{A_{79F} A_{101RF}} (DER2F)^2 (DER1F)^2 - \frac{A_{29} A_{49R} A_{100}}{A_{101RF}} Y_6 \quad \text{(D-999)}$$

[6]Again, the proper sign s_7 and the appropriate angle α, depending on entrance or exit coupled motion, must be chosen.

$$A_{136} = A_{51} A_{31} U - \frac{A_{29} A_{49R} A_{81} A_{102RF}}{A_{79F} A_{101RF}} (DER2R)(DER1F)$$

$$- \frac{A_{29} A_{49R} A_{104}}{A_{101RF}} DER2R \tag{D-1000}$$

$$A_{137} = A_{29} A_{50} - A_{51} (A_9 + A_{30})$$

$$+ \frac{A_{29} A_{49R}}{A_{101RF}} \left\{ \frac{A_{102RF}}{A_{79R}} [A_{80} + A_{60}] - A_{103} + A_{99} \right\} \tag{D-1001}$$

$$A_{138} = - \frac{A_{29} A_{49R} A_{102RF}}{A_{101RF} A_{79F}} m_1 r_{c1} \tag{D-1002}$$

$$A_{139} = A_{51} m_p r_{cp} \tag{D-1003}$$

Contact Forces

The contact force F_{23RF} is given by equation D-994 [note new subscript]

$$F_{23RF} = \frac{A_{140} \ddot{\phi} + A_{141} \dot{\phi}^2 + A_{142} \dot{\phi} + A_{143}}{A_{101RF}} \tag{D-1004}$$

where

$$A_{140} = \frac{A_{102RF} l_{1R} Y_3 Y_5}{A_{79F}} + A_{100} Y_5 \tag{D-1005}$$

$$A_{141} = \frac{A_{102RF}}{A_{79F}} \Big[l_{1R} [Y_3 Y_6 + Y_4 (DER2R)^2]$$

$$+ A_{82} (DER2R)^2 (DER1F)^2 \Big] + A_{100} Y_6 \tag{D-1006}$$

$$A_{142} = \frac{A_{102RF} A_{81}}{A_{79F}} (DER2R)(DER1F) + A_{104} (DER2R) \tag{D-1007}$$

$$A_{143} = \frac{A_{102RF}}{A_{79F}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin\gamma - O_y \cos\gamma)] - A_{103} + A_{99} \tag{D-1008}$$

The contact force $F_{12RF} = F_{12F}$, i.e., equation D-593, is now expressed in terms of the angular velocity $\dot{\phi}$ and the angular acceleration $\ddot{\phi}$, which corresond to the RF contact mode, according to equations F-146 and F-147, respectively

$$F_{12RF} = \frac{1}{A_{79F}}\Big\{ I_{1R}\left[\ddot{\phi}(Y_3 Y_5) + \dot{\phi}^2 (Y_3 Y_6 + Y_4 (DER2R)^2)\right]$$

$$+ A_{81}\ddot{\phi}(DER1F)(DER2R) + A_{82}\dot{\phi}^2((DER1F)^2(DER2R)^2$$

$$+ A_{80} + A_{60} - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma)\Big\} \tag{D-1009}$$

or

$$F_{12RF} = \frac{A_{144}\ddot{\phi} + A_{145}\dot{\phi}^2 + A_{146}\dot{\phi} + A_{147}}{A_{79F}} \tag{D-1010}$$

where

$$A_{144} = I_{1R}Y_3Y_5 \tag{D-1011}$$

$$A_{145} = I_{1R}\left[Y_3Y_6 + Y_4(DER2R)^2\right] + A_{82}(DER1F)^2(DER2R)^2 \tag{D-1012}$$

$$A_{146} = A_{81}(DER1F)(DER2R) \tag{D-1013}$$

$$A_{147} = A_{80} + A_{60} - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma) \tag{D-1014}$$

The contact force P_n, between the verge and the escape wheel, may be found in terms of $\psi(t)$ with the help of equation D-967 again.

If it is desired to obtain P_n in terms of the applicable $\phi(t)$, one substitutes equation D-1004 for $F_{23RF} = F_{23}$ into equation D-239 or equation D-364. Again, it must be kept in mind that $A_{51} = A_{51R} = AA_{51R}$. Then

$$P_n = \frac{I_{zs}\ddot{\phi} + A_{48}\dot{\phi}^2 + F_{23RF}A_{49R} + A_{50}}{A_{51}} \tag{D-1015}$$

For the contact forces F_{23RF}, F_{12RF}, and the above P_n, the values of $\ddot{\phi}$ and $\dot{\phi}$ must be those associated with the differential equation D-997, which deals with the RF contact mode.

DYNAMICS OF COMBINED SYSTEM IN COUPLED MOTION WITH MESH NO. 2 IN ROUND-ON-FLAT CONTACT AND MESH NO. 1 IN ROUND-ON-ROUND CONTACT (FR)

Combined Differential Equations

To obtain a single differential equation for the total system in coupled motion and FR contact, equation D-537 for F_{12} is first substituted into equation D-941 for F_{23F}

$$F_{23F}A_{101FR} = \frac{A_{102FR}}{A_{79R}}[I_{1R}\ddot{\phi}_1 + A_{81}\dot{\phi}_1 + A_{82}\dot{\phi}_1^2 + A_{80} + A_{60}$$

$$- m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma)]$$

$$- A_{103} + A_{104}\dot{\phi}_2 + A_{99} + A_{100}\ddot{\phi}_2 \qquad \text{(D-1016)}$$

Equations F-126 and F-131 of appendix F are now substituted for $\dot{\phi}_2$ and $\ddot{\phi}_2$, respectively. Similarly, equations F-154 and F-155 serve for $\dot{\phi}_1$ and $\ddot{\phi}_1$ in turn.

$$F_{23F} = \frac{1}{A_{101FR}}\left\{\frac{A_{102FR}}{A_{79R}}\Big[I_{1R}[\ddot{\phi}Y_1 Y_7 + \dot{\phi}^2(Y_1 Y_8 + Y_2(DER2F)^2)]\right.$$

$$+ A_{81}\dot{\phi}(DER1R)(DER2F) + A_{82}\dot{\phi}^2(DER1R)^2(DER2F)^2$$

$$+ A_{80} + A_{60} - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma)]$$

$$\left. - A_{103} + A_{104}\dot{\phi}DER2F + A_{99} + A_{100}[\ddot{\phi}Y_7 + \dot{\phi}^2 Y_8]\right\} \qquad \text{(D-1017)}$$

The above expression for F_{23F} is now substituted into equation D-403, the combined escapement coupled motion equation, with mesh no. 2 in round-on-flat contact

$$[A_{51}I_{PR}U - A_{29}I_{zs}]\ddot{\phi} + [A_{51}(A_{32}U^2 + I_{PR}V) - A_{29}A_{48}]\dot{\phi}^2 + A_{51}A_{31}U\dot{\phi}$$

$$= A_{29}A_{50} - A_{51}(A_9 + A_{30}) + A_{51}m_P r_{cp}(K_x \sin\beta - K_y \cos\beta)$$

$$+ \frac{A_{29}A_{49F}}{A_{101FR}}\left\{\frac{A_{102FR}}{A_{79R}}\Big[I_{1R}[\ddot{\phi}Y_1 Y_7 + \dot{\phi}^2(Y_1 Y_8 + Y_2(DER2F)^2)]\right.$$

$$+ A_{81}\dot{\phi}(DER1R)(DER2F) + A_{82}\dot{\phi}^2(DER1R)^2(DER2F)^2 + A_{80} + A_{60}$$

$$- m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma)\Big] - A_{103} + A_{104}\dot{\phi}DER2F$$

$$\left. + A_{99} + A_{100}[\ddot{\phi}Y_7 + \dot{\phi}^2 Y_8]\right\} \qquad \text{(D-1018)}$$

Again, the coefficients of like terms are collected

$$\ddot{\phi}\left[A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{29} A_{49F} A_{102FR}}{A_{101FR} A_{79R}} I_{1R} Y_1 Y_7 - \frac{A_{29} A_{49F} A_{100}}{A_{101FR}} Y_7\right]$$

$$+ \dot{\phi}^2\left[A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48} - \frac{A_{29} A_{49F}}{A_{101FR}}\left\{\frac{A_{102FR}}{A_{79F}}\left[I_{1R} [Y_1 Y_8 + Y_2 (DER2F)^2]\right.\right.\right.$$

$$\left.\left.\left. + A_{82} (DER1R)^2 (DER2F)^2\right] + A_{100} Y_8\right\}\right]$$

$$+ \dot{\phi}\left[A_{51} A_{31} U - \frac{A_{29} A_{49F}}{A_{101FR}}\left\{\frac{A_{102FR}}{A_{79R}} A_{81} (DER1R)(DER2F) + A_{104} DER2F\right\}\right]$$

$$= A_{29}A_{50} - A_{51}(A_9 + A_{30}) + A_{51}m_p r_{cp}(K_x \sin\beta - K_y \cos\beta)$$

$$+ \frac{A_{29} A_{49F}}{A_{101FR}}\left\{\frac{A_{102FR}}{A_{79R}} [A_{80} + A_{60} - m_1 r_{c1} (O_x \sin\gamma - O_y \cos\gamma)] - A_{103} + A_{99}\right\} \qquad \text{(D-1019)}$$

The above is now rewritten as[7]

$$A_{148} \ddot{\phi} + A_{149} \dot{\phi}^2 + A_{150} \dot{\phi} = A_{151} + A_{152} (O_x \sin\gamma - O_y \cos\gamma)$$

$$+ A_{153} (K_x \sin\beta - K_y \cos\beta) \qquad \text{(D-1020)}$$

where

$$A_{148} = A_{51} I_{PR} U - A_{29} I_{zs} - \frac{A_{29} A_{49F}}{A_{101FR}}\left\{\frac{A_{102FR} I_{1R} Y_1 Y_7}{A_{79R}} + A_{100} Y_7\right\} \qquad \text{(D-1021)}$$

[7]As before, entrance or exit contact depends on s_7 and α.

$$A_{149} = A_{51}(A_{32}U^2 + I_{PR}V) - A_{29}A_{48}$$

$$- \frac{A_{29}A_{49F}}{A_{101FR}}\left\{\frac{A_{102FR}}{A_{79R}}\left[I_{1R}[Y_1Y_8 + Y_2(DER2F)^2]\right.\right.$$

$$\left.\left. + A_{82}(DER1R)^2(DER2F)^2\right] + A_{100}Y_8\right\} \quad \text{(D-1022)}$$

$$A_{150} = A_{51}A_{31}U - \frac{A_{29}A_{49F}}{A_{101FR}}\left\{\frac{A_{102FR}}{A_{79R}}A_{81}(DER1R)(DER2F)\right.$$

$$\left. + A_{104}DER2F\right\} \quad \text{(D-1023)}$$

$$A_{151} = A_{29}A_{50} - A_{51}(A_9 + A_{30})$$

$$+ \frac{A_{29}A_{49F}}{A_{101FR}}\left\{\frac{A_{102FR}}{A_{79R}}[A_{80} + A_{60}] - A_{103} + A_{99}\right\} \quad \text{(D-1024)}$$

$$A_{152} = - \frac{A_{29}A_{49F}A_{102FR}}{A_{101FR}A_{79R}}m_1 r_{c1} \quad \text{(D-1025)}$$

$$A_{153} = A_{51}m_p r_{cp} \quad \text{(D-1026)}$$

Contact Forces

The contact force F_{23FR} is given by equation D-1017 [note new subscript]

$$F_{23FR} = \frac{A_{154}\ddot{\phi} + A_{155}\dot{\phi}^2 + A_{156}\dot{\phi} + A_{157}}{A_{101FR}} \quad \text{(D-1027)}$$

where

$$A_{154} = \frac{A_{102FR}}{A_{79R}}I_{1R}Y_1Y_7 + A_{100}Y_7 \quad \text{(D-1028)}$$

$$A_{155} = \frac{A_{102FR}}{A_{79R}}\Big\{ I_{1R}(Y_1 Y_8 + Y_2 (DER2F)^2)$$

$$+ A_{82}(DER1R)^2 (DER2F)^2 \Big\} + A_{100} Y_8 \tag{D-1029a}$$

$$A_{156} = \frac{A_{102FR}}{A_{79R}} A_{81}(DER1R)(DER2F) + A_{104}(DER2F) \tag{D-1029b}$$

$$A_{157} = \frac{A_{102FR}}{A_{79R}} [A_{80} + A_{60} - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma)]$$

$$- A_{103} + A_{99} \tag{D-1030}$$

The contact force $F_{12FR} = F_{12}$, i.e., equation D-537, is now expressed in terms of the angular velocity $\dot{\phi}$ and the angular acceleration $\ddot{\phi}$ which corresond to the FR contact mode. Thus, with equations F-154 and F-155, one obtains

$$F_{12FR} = \frac{1}{A_{79R}}\Big\{ I_{1R}\big[\ddot{\phi}(Y_1 Y_7) + \dot{\phi}^2 [Y_1 Y_8 + Y_2 (DER2F)^2]\big]$$

$$+ A_{81}\dot{\phi}(DER1R)(DER2F) + A_{82}\dot{\phi}^2 (DER1R)^2 (DER2F)^2$$

$$+ A_{80} + A_{60} - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma) \Big\} \tag{D-1031}$$

or

$$F_{12FR} = \frac{A_{158}\ddot{\phi} + A_{159}\dot{\phi}^2 + A_{160}\dot{\phi} + A_{161}}{A_{79R}} \tag{D-1032}$$

where

$$A_{158} = I_{1R} Y_1 Y_7 \tag{D-1033}$$

$$A_{159} = I_{1R}[Y_1 Y_8 + Y_2 (DER2F)^2] + A_{82}(DER1R)^2 (DER2F)^2 \tag{D-1034}$$

$$A_{160} = A_{81}(DER1R)(DER2F) \tag{D-1035}$$

$$A_{161} = A_{80} + A_{60} - m_1 r_{c1}(O_x \sin\gamma - O_y \cos\gamma) \qquad \text{(D-1036)}$$

The contact force P_n, between the verge and the escape wheel, may again be found in terms of $\psi(t)$ with the help of equation D-967.

If it is desired to obtain P_n in terms of the applicable $\phi(t)$, one substitutes equation D-1027 for $F_{23FR} = F_{23F}$ into equation D-322 or equation D-395 keeping in mind that $A_{51} = A_{51F} = AA_{51F}$. Then

$$P_n = \frac{I_{zs}\ddot{\phi} + A_{48}\dot{\phi}^2 + F_{23FR}A_{49F} + A_{50}}{A_{51}} \qquad \text{(D-1037)}$$

For the contact forces F_{23FR}, F_{12FR}, and P_n (above), the values of $\ddot{\phi}$ and $\dot{\phi}$ must be those associated with the differential equation D-1020, which deals with the FR contact mode.

DYNAMICS OF FREE MOTION

Pallet Free Motion Differential Equation

Regardless of gear tooth contact condition, the free motion equation of the pallet is obtained by letting $P_n = 0$ in equation D-967. Then

$$I_{PR}\ddot{\psi} + A_{32}\dot{\psi}^2 + A_{31}\dot{\psi} = -A_{119} + m_p r_{cp}\left(K_x \sin\beta - K_y \cos\beta\right) \qquad \text{(D-1038)}$$

Escape Wheel--Gear Train--Rotor Free Motion Conditions for RR Contact

Combined Differential Equation

To obtain the combined free motion differential equation for the RR contact, equation D-969 for P_n is first set equal to zero. Then

$$I_{zs}\ddot{\phi} + A_{48R}\dot{\phi}^2 + F_{23RR}A_{49R} + A_{50R} = 0 \qquad \text{(D-1039)}$$

Note that his expression is not dependent on entrance or exit anymore.

Equation D-956 is now substituted for F_{23RR}

$$I_{zs}\ddot{\phi} + A_{48}\dot{\phi}^2 + \frac{A_{49R}}{A_{101RR}}\left[A_{111}\ddot{\phi} + A_{112}\dot{\phi}^2 + A_{113}\dot{\phi} + A_{114}\right] + A_{50} = 0$$

or

$$A_{162}\ddot{\phi} + A_{163}\dot{\phi}^2 + A_{164}\dot{\phi} + A_{165} = 0 \tag{D-1040}$$

where

$$A_{162} = I_{zs} + \frac{A_{49R}A_{111}}{A_{101RR}} \tag{D-1041}$$

$$A_{163} = A_{48} + \frac{A_{49R}A_{112}}{A_{101RR}} \tag{D-1042}$$

$$A_{164} = \frac{A_{49R}A_{113}}{A_{101RR}} \tag{D-1043}$$

$$A_{165} = A_{50} + \frac{A_{49R}A_{114}}{A_{101RR}} \tag{D-1044}$$

Contact Force T_{23RR}

In order to differentiate the contact forces during free motion from those during coupled motion the nomenclature T is now introduced.

While T_{23RR} will have the same form as F_{23RR}, it must be kept in mind that $\ddot{\phi}$ and $\dot{\phi}$ now correspond to the free motion values of differential equation D-1040. Thus, with equation D-1039

$$T_{23RR} = -\frac{(I_{zs}\ddot{\phi} + A_{48}\dot{\phi}^2 + A_{50})}{A_{49R}} \tag{D-1045}$$

Contact Force T_{12RR}

The form of contact force T_{12RR} is identical to that of contact force F_{12RR} of equation D-962, i.e.

$$T_{12RR} = \frac{A_{115}\ddot{\phi} + A_{116}\dot{\phi}^2 + A_{117}\dot{\phi} + A_{118}}{A_{78R}} \tag{D-1046}$$

Again, the values of $\ddot{\phi}$ and $\dot{\phi}$ must correspond to those obtained from the solution of equation D-1040.

Escape Wheel--Gear Train--Rotor Free Motion Conditions for FF Contact

Combined Differential Equation

To obtain the combined differential equation for the FF contact mode, equation D-992 for the applicable form of P_n is first set equal to zero. Then

$$I_{zs}\ddot{\phi} + A_{48}\dot{\phi}^2 + F_{23FF}A_{49F} + A_{50} = 0 \tag{D-1047}$$

Equation D-981 is then substituted for F_{23FF}

$$I_{zs}\ddot{\phi} + A_{48F}\dot{\phi}^2 + \frac{A_{49F}}{A_{101FF}}[A_{126}\ddot{\phi} + A_{127}\dot{\phi} + A_{128}\dot{\phi} + A_{129}] + A_{50} = 0$$

or

$$A_{166}\ddot{\phi} + A_{167}\dot{\phi}^2 + A_{168}\dot{\phi} + A_{169} = 0 \tag{D-1048}$$

where

$$A_{166} = I_{zs} + \frac{A_{49F}A_{126}}{A_{101FF}} \tag{D-1049}$$

$$A_{167} = A_{48} + \frac{A_{49F}A_{127}}{A_{101FF}} \tag{D-1050}$$

$$A_{168} = \frac{A_{49F}A_{128}}{A_{101FF}} \tag{D-1051}$$

$$A_{169} = \frac{A_{49F}A_{129}}{A_{101FF}} + A_{50} \tag{D-1052}$$

Contact Force T_{23FF}

The force T_{23FF} has the same form as F_{23FF}, as obtained from equation D-1047, i.e.

$$T_{23FF} = -\frac{(I_{zs}\ddot{\phi} + A_{48}\dot{\phi}^2 + A_{50})}{A_{49F}} \tag{D-1053}$$

Note that $\ddot{\phi}$ and $\dot{\phi}$ must come from equation D-1048.

Contact Force T_{12FF}

The form of contact force T_{12FF} is identical to that of contact force F_{12FF} of equation D-987, i.e.

$$T_{12FF} = \frac{A_{130}\ddot{\phi} + A_{131}\dot{\phi}^2 + A_{132}\dot{\phi} + A_{133}}{A_{79F}} \tag{D-1054}$$

Again, $\ddot{\phi}$ and $\dot{\phi}$ must come from equation D-1048.

Escape Wheel--Gear Train--Rotor Free Motion Conditions for RF Contact

Combined Differential Equation

To obtain the combined differential equation for the RF contact mode, P_n in equation D-1015 is first set equal to zero. This results in

$$I_{zs}\ddot{\phi} + A_{48}\dot{\phi}^2 + F_{23RF}A_{49R} + A_{50} = 0 \tag{D-1055}$$

Equation D-1004 for F_{23RF} is then substituted into the above

$$I_{zs}\ddot{\phi} + A_{48F}\dot{\phi}^2 + \frac{A_{49R}}{A_{101RF}}\left[A_{140}\ddot{\phi} + A_{141}\dot{\phi}^2 + A_{142}\dot{\phi} + A_{143}\right] + A_{50} = 0$$

or

$$A_{170}\ddot{\phi} + A_{171}\dot{\phi}^2 + A_{172}\dot{\phi} + A_{173} = 0 \tag{D-1056}$$

where

$$A_{170} = I_{zs} + \frac{A_{49R} A_{140}}{A_{101RF}} \tag{D-1057}$$

$$A_{171} = A_{48} + \frac{A_{49R} A_{141}}{A_{101RF}} \tag{D-1058}$$

$$A_{172} = \frac{A_{49R} A_{142}}{A_{101RF}} \tag{D-1059}$$

$$A_{173} = \frac{A_{49R} A_{143}}{A_{101RF}} + A_{50} \tag{D-1060}$$

Contact Force T_{23RF}

The contact force T_{23RF} has the same form as F_{23RF}, as obtained from equation D-1055. Thus

$$T_{23RF} = - \frac{(I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + A_{50})}{A_{49R}} \tag{D-1061}$$

Note that $\ddot{\phi}$ and $\dot{\phi}$ must now come from equation D-1056.

Contact Force T_{12RF}

The form of contact force T_{12RF} is identical to that of contact force F_{12RF} of equation D-1010, i.e.

$$T_{12RF} = \frac{A_{144} \ddot{\phi} + A_{145} \dot{\phi}^2 + A_{146} \dot{\phi} + A_{147}}{A_{79F}} \tag{D-1062}$$

Again, $\ddot{\phi}$ and $\dot{\phi}$ must be obtained from equation D-1056.

Escape Wheel--Gear Train--Rotor Free Motion Conditions for FR Contact

Combined Differential Equation

To obtain the combined differential equation for the FR contact mode, P_n in equation D-1037 is first set equal to zero. This leads to

$$I_{zs}\ddot{\phi} + A_{48}\dot{\phi}^2 + F_{23FR}A_{49F} + A_{50} = 0 \tag{D-1063}$$

Equation D-1027 for F_{23FR} is subsequently substituted into the above

$$I_{zs}\ddot{\phi} + A_{48}\dot{\phi}^2 + \frac{A_{49F}}{A_{101FR}}\left[A_{154}\ddot{\phi} + A_{155}\dot{\phi}^2 + A_{156}\dot{\phi} + A_{157}\right] + A_{50} = 0$$

or

$$A_{174}\ddot{\phi} + A_{175}\dot{\phi}^2 + A_{176}\dot{\phi} + A_{177} = 0 \tag{D-1064}$$

where

$$A_{174} = I_{zs} + \frac{A_{49F}A_{154}}{A_{101FR}} \tag{D-1065}$$

$$A_{175} = A_{48} + \frac{A_{49F}A_{155}}{A_{101FR}} \tag{D-1066}$$

$$A_{176} = \frac{A_{49F}A_{156}}{A_{101FR}} \tag{D-1067}$$

$$A_{177} = \frac{A_{49F}A_{157}}{A_{101FR}} + A_{50} \tag{D-1068}$$

Contact Force T_{23FR}

The force T_{23FR} has the same form as F_{23FR}, if obtained from equation D-1063, i.e.

$$T_{23FR} = -\frac{(I_{zs}\ddot{\phi} + A_{48}\dot{\phi}^2 + A_{50})}{A_{49F}} \tag{D-1069}$$

Here, $\ddot{\phi}$ and $\dot{\phi}$ must come from equation D-1064.

Contact Force T_{12FR}

The form of contact force T_{12FR} is identical to that of contact force F_{12FR} of equation D-1032, i.e.

$$T_{12FR} = \frac{A_{158}\ddot{\phi} + A_{159}\dot{\phi}^2 + A_{160}\dot{\phi} + A_{161}}{A_{79R}} \qquad \text{(D-1070)}$$

Again, $\ddot{\phi}$ and $\dot{\phi}$ must be obtained from solution of the differential equation D-1064.

IMPACT EQUATIONS

The basic impact formulation may be taken directly from references 1 and 2. It must be realized that, the pre-impact angular velocity $\dot{\phi}_i$ of the escape wheel must correspond to the governing gear contact regime of free motion.

As in the above references, angle α_{EN} must be used for entrance impact, while for exit impact the angle α_{EX} is applicable. With both entrance and exit impact having the same form, one uses

$$\dot{\phi}_f = \frac{\dot{\phi}_i\left(I_{STOT}D_1'^2 - e_r I_{\zeta\zeta P}A_1'^2\right) + \dot{\psi}_i I_{\zeta\zeta P}A_1'(1 + e_r)D_1'}{I_{\zeta\zeta P}A_1'^2 + I_{STOT}D_1'^2} \qquad \text{(D-1071)}$$

and

$$\dot{\psi}_f = \frac{\dot{\phi}_f A_1' - e_r\left(\dot{\psi}_i D_1' - \dot{\phi}_i A_1'\right)}{D_1'} \qquad \text{(D-1072)}$$

where I_{STOT}, the free motion escape wheel--gear train--rotor moment of inertia as referred to the escape wheel, depends on the gear contact regime.

RR Contact

With equations F-108 and F-142 of appendix F

$$I_{STOT} = I_{zs} + I_{z2}DER2R^2 + I_{\zeta\zeta_1}(DER2R)^2(DER1R)^2 \qquad \text{(D-1073)}$$

FF Contact

With equations F-126 and F-150

$$I_{STOT} = I_{zs} + I_{z2}DER2F^2 + I_{\zeta\zeta_1}(DER1F)^2(DER2F)^2 \qquad \text{(D-1074)}$$

RF Contact

With equations F-108 and F-146

$$I_{STOT} = I_{zs} + I_{z2}DER2R^2 + I_{\zeta\zeta_1}(DER2R)^2(DER1F)^2 \qquad \text{(D-1075)}$$

FR Contact

With equations F-126 and F-154

$$I_{STOT} = I_{zs} + I_{z2}DER2F^2 + I_{\zeta\zeta_1}(DER2F)^2(DER1R)^2 \qquad \text{(D-1076)}$$

REFERENCES

1. Lowen, G. G. and Tepper, F. R., "Computer Simulation of Artillery S&A Mechanisms (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-82013, ARRADCOM, Dover, NJ, November 1982.

2. Tepper, F. R. ano Lowen, G. G., "Computer Simulation of Artillery Safing and Arming Mechanism in Aeroballistic Environment (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-83050, ARDC, Dover, NJ, July 1984.

3. Shames, I. H., Engineering Mechanics, Statics, and Dynamics, Third Edition, Prentice Hall, Inc., Englewood Cliffs, NJ, 1980.

4. Lowen, G. G. and Tepper, F. R., "Computer Simulations of Artillery S&A Mechanisms (Involute Gear Train and Pin Pallet Runaway Escapement)," Technical Report ARLCD-TR-81039, ARRADCOM, Dover, NJ, July 1982.

5. Lowen, G. G. and Tepper, F. R., "Fuze Gear Train Analysis," Technical Report ARLCD-TR-79030, ARRADCOM, Dover, NJ, December 1979.

APPENDIX E

PROJECTILE KINEMATICS

Until the time when actual aeroballistic data can be incorporated into program AERCLOC, the following expressions for the projectile kinematics will be used*

Spin Simulation

Assuming a constant spin velocity, obtain for the spin kinematics:

$$\ddot{\phi}_E = 0 \tag{E-1}$$

$$\dot{\phi}_E = DPHIE = \frac{RPM \times 2\pi}{60} \tag{E-2}$$

and

$$\phi_E = PHIE = \dot{\phi}_E t \tag{E-3}$$

Precession Simulation

Assuming that the precession velocity is also constant, the following is obtained

$$\ddot{\psi}_E = 0 \tag{E-4}$$

where

$$\dot{\psi}_E = DPSIE = \frac{DPHIE}{KP} \tag{E-5}$$

$KP = K_p$, is a divisor to obtain the precession velocity as a fraction of the spin velocity

$$K_p \approx 100 \tag{E-6}$$

$$\psi_E = PSIE = \dot{\psi}_E t \tag{E-7}$$

Nutation Simulation

The nutation angle is assumed to vary sinusoidally about some initial angle. Then

$$\theta_E = THET = THETIN + TVAR \sin(K_n \dot{\psi}_E t) \tag{E-8}$$

*For nomenclature see appendix A.

where

THETIN $\approx$ 8 degrees, the initial cone angle (E-9)

TVAR $\approx$ 2 degrees, the maximum change in cone angle (E-10)

$K_n \approx$ 6 to 8, multiplier of precession angular velocity $\dot{\psi}_E$ to obtain maximum nutation velocity $\dot{\theta}_{EMAX}$ (E-11)

With the above

$$\dot{\theta}_E = TVAR * K_n * \dot{\psi}_E \cos (K_n \dot{\psi}_E t) \qquad \text{(E-12)}$$

$$\ddot{\theta}_E = - TVAR * K_n^2 * \dot{\psi}_E^2 \sin (K_n \dot{\psi}_E t) \qquad \text{(E-13)}$$

Drag Deceleration

The deceleration $\ddot{\bar{z}} = \ddot{z}\bar{k}$ of the center of mass, due to drag and expressed in the projectile-fixed system, is given by

$$\ddot{z} = DDZ = -386.4 * 10 \qquad \text{(E-14)}$$

APPENDIX F

FORWARD AND REVERSE KINEMATICS OF CLOCK GEAR MESHES NO. 1 AND NO. 2

The present appendix restates for, the sake of convenience, various expressions pertaining to the forward as well as the reverse kinematics of meshes 1 and 2, which were originally derived in references 1 and 2, respectively.

The angle between the escape wheel pinion tooth centerline and the x-axis is now called ϕ_s.

Subsequently, the angular velocities and accelerations of gear and pinion no. 2 and rotor gear no. 1 will be formulated in terms of the angular velocity and the angular acceleration of the escape wheel for all regime combinations.

Forward Kinematics of Mesh No. 1 (angle ϕ_1 is input, angle ϕ_{2P} is output)[1]

Round-on-Round Phase of Motion (fig. F-1)

Angle ϕ_{2P}. The angle ϕ_{2P} may be obtained from

$$\phi_{2P} = 2 \tan^{-1} \frac{A_{1R} \pm \sqrt{A_{1R}^2 + B_{1R}^2 - C_{1R}^2}}{B_{1R} + C_{1R}} \tag{F-1}$$

where

$$A_{1R} = b_1 \sin(\beta_1 + \delta_{P1}) - a_{G1} \sin(\phi_1 - \delta_{G1} + \delta_{P1}) \tag{F-2}$$

$$B_{1R} = b_1 \cos(\beta_1 + \delta_{P1}) - a_{G1} \cos(\phi_1 - \delta_{G1} + \delta_{P1}) \tag{F-3}$$

$$C_{1R} = \frac{L_1^2 - b_1^2 - a_{G1}^2 - a_{P1}^2 + 2a_{G1} b_1 \cos(\phi_1 - \delta_{G1} - \beta_1)}{2a_{P1}} \tag{F-4}$$

The correct sign in equation F-1 must be determined by geometric considerations.

Angle λ_1

$$\lambda_1 = \cos^{-1}\left[\frac{b_1 \cos\beta_1 + a_{P1} \cos(\phi_{2P} - \delta_{P1}) - a_{G1} \cos(\phi_1 - \delta_{G1})}{L_1}\right] \tag{F-5}$$

---

[1]The output angle of mesh 1 is called ϕ_{2P} (P= pinion), while the input angle of mesh 2 will be ϕ_{2G} (G = gear). Only the increments of these angles are equal.

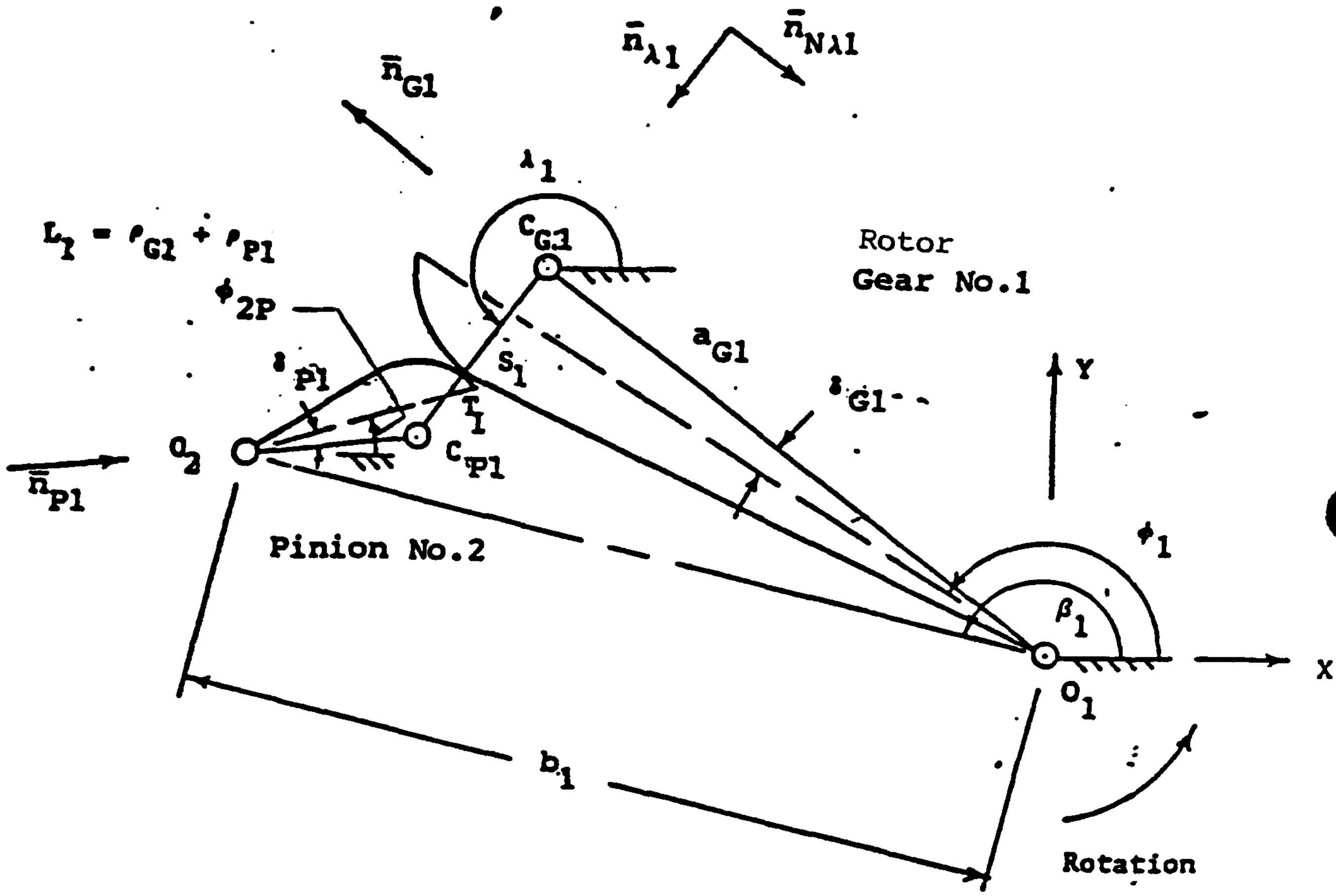


Figure F-1. Round-on-round phase of motion for mesh no. 1

$$\lambda_1 = \sin^{-1}\left[\frac{b_1 \sin\beta_1 + a_{P1} \sin(\phi_{2P} - \delta_{P1}) - a_{G1} \sin(\phi_1 - \delta_{G1})}{L_1}\right] \tag{F-6}$$

Output Angular Velocity[2] $\dot{\phi}_2 = \dot{\phi}_{2P} = \dot{\phi}_{2G}$

$$\dot{\phi}_2 = \dot{\phi}_1\left[\frac{L_{1R}}{M_{1R}}\right] \tag{F-7}$$

where

$$L_{1R} = A_{1RD} \sin\phi_{2P} - B_{1RD} \cos\phi_{2P} - C_{1RD} \tag{F-8}$$

$$M_{1R} = A_{1R} \cos\phi_{2P} - B_{1R} \sin\phi_{2P} \tag{F-9}$$

with

$$A_{1RD} = a_{G1} \cos(\phi_1 - \delta_{G1} + \delta_{P1}) \tag{F-10}$$

$$B_{1RD} = a_{G1} \sin(\phi_1 - \delta_{G1} + \delta_{P1}) \tag{F-11}$$

$$C_{1RD} = \frac{a_{G1}\, b_1 \sin(\phi_1 - \delta_{G!} - \beta_1)}{a_{P1}} \tag{F-12}$$

Relative Velocity $V_{S1/T1_R}$ at the Contact Point

$$\begin{aligned}\bar{V}_{S1/T1_R} = \Big\{&\dot{\phi}_1 \left[a_{G1} \cos(\phi_1 - \delta_{G1} - \lambda_1) + \rho_{G1}\right] \\ &- \dot{\phi}_2 \left[a_{P1} \cos(\phi_{2P} - \delta_{P1} - \lambda_1) - \rho_{P1}\right]\Big\}\, \bar{n}_{N\lambda 1}\end{aligned} \tag{F-13}$$

[2]Regarding the derivatives of the gear and pinion no. 2, there is no difference whether the gear or the pinion is involved. The difference is only needed for the angles, since the angles ϕ_{2P} and ϕ_{2G} are expressed with respect to different center lines.

Round-on Flat Phase of Motion (fig. F-2)

Angle ϕ_{2P}

$$\phi_{2P} = 2\tan^{-1}\frac{A_{1F} \pm \sqrt{A_{1F}^2 + B_{1F}^2 - C_{1F}^2}}{B_{1F} + C_{1F}} \tag{F-14}$$

with appropriate choice of sign, and

$$A_{1F} = a_{G1}\cos(\phi_1 - \delta_{G1} - \alpha_{P1}) - b_1\cos(\beta_1 - \alpha_{P1}) \tag{F-15}$$

$$B_{1F} = -a_{G1}\sin(\phi_1 - \delta_{G1} - \alpha_{P1}) + b_1\sin(\beta_1 - \alpha_{P1}) \tag{F-16}$$

$$C_{1F} = -\rho_{G1} \tag{F-17}$$

Distance g_1

$$g_1 = \frac{a_{G1}\sin(\phi_1 - \delta_{G1}) - \rho_{G1}\cos(\phi_{2P} + \alpha_{P1}) - b_1\sin\beta_1}{\sin(\phi_{2P} + \alpha_{P1})} \tag{F-18}$$

Output Angular Velocity $\dot{\phi}_2 = \dot{\phi}_{2P} = \dot{\phi}_{2G}$

$$\dot{\phi}_2 = \dot{\phi}_1\frac{L_{1F}}{M_{1F}} \tag{F-19}$$

where

$$L_{1F} = A_{1FD}\sin\phi_{2P} + B_{1FD}\cos\phi_{2P} \tag{F-20}$$

$$M_{1F} = A_{1F}\cos\phi_{2P} - B_{1F}\sin\phi_{2P} \tag{F-21}$$

and

$$A_{1FD} = a_{G1}\sin(\phi_1 - \delta_{G1} - \alpha_{P1}) \tag{F-22}$$

$$B_{1FD} = a_{G1}\cos(\phi_1 - \delta_{G1} - \alpha_{P1}) \tag{F-23}$$

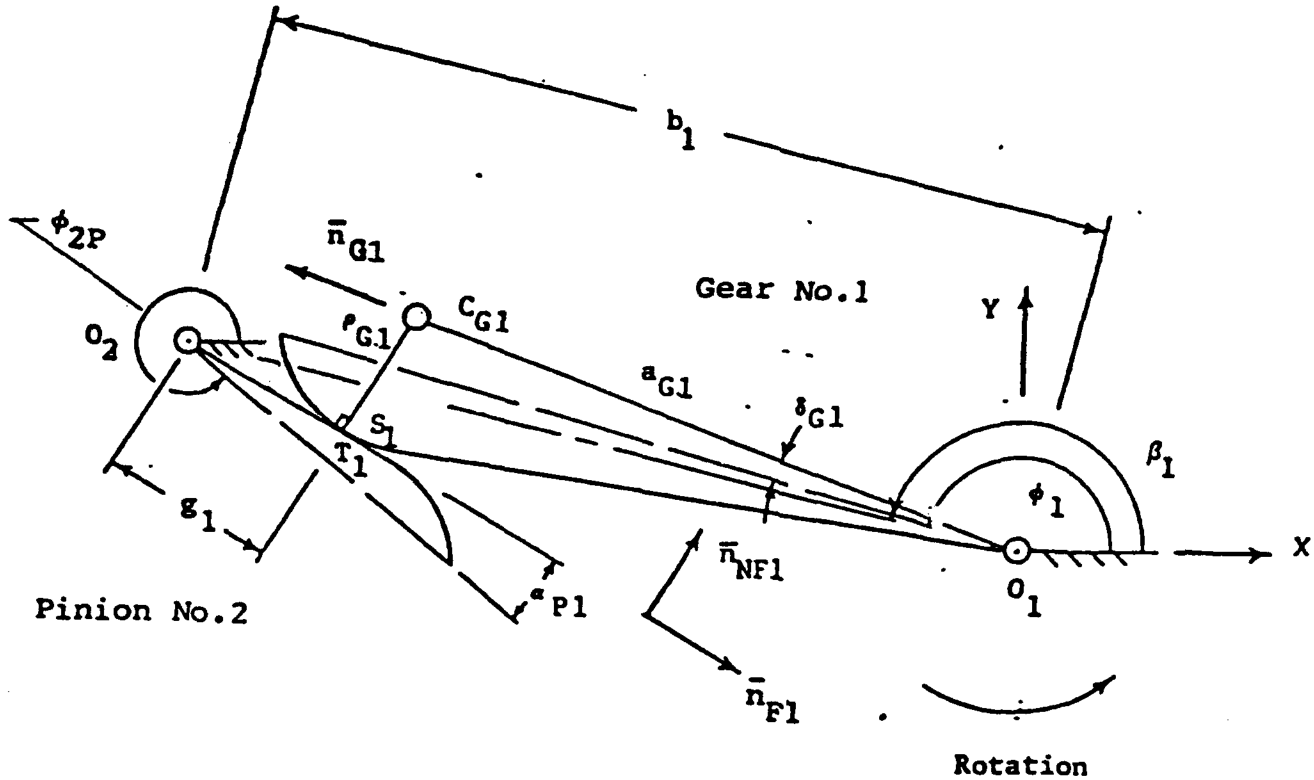


Figure F-2. Round-on-flat phase of motion of mesh no. 1

Relative Velocity $\bar{V}_{S1/T1_F}$ at Contact Point

$$\bar{V}_{S1/T1_F} = \dot{\phi}_1 \{a_{G1} \sin(\phi_{2P} + \alpha_{P1} - \phi_1 + \delta_{G1}) + \rho_{G1}\} \bar{n}_{F1} \quad \text{(F-24)}$$

Transition Angles ϕ_{2PT} and ϕ_{1T}

$$\phi_{2PT} = 2 \tan^{-1} \frac{A_{1T} \pm \sqrt{A_{1T}^2 + B_{1T}^2 - C_{1T}^2}}{B_{1T} + C_{1T}} \quad \text{(F-25)}$$

with appropriate choice of sign, and

$$A_{1T} = -\rho_{G1} \cos(\beta_1 - \alpha_{P1}) + f_{P1} \sin(\beta_1 - \alpha_1) \quad \text{(F-26)}$$

$$B_{1T} = \rho_{G1} \sin(\beta_1 - \alpha_{P1}) + f_{P1} \cos(\beta_1 - \alpha_{P1}) \quad \text{(F-27)}$$

$$C_{1T} = \frac{a_{G1}^2 - \rho_{G1}^2 - b_1^2 - f_{P1}^2}{2b_1} \quad \text{(F-28)}$$

$$\phi_{1T} = \cos^{-1}\left[\frac{-\rho_{G1} \sin(\phi_{2PT} + \alpha_{P1}) + b_1 \cos\beta_1 + f_{P1} \cos(\rho_{2PT} + \alpha_{P1})}{a_{G1}}\right] + \delta_{G1} \quad \text{(F-29)}$$

$$\phi_{1T} = \sin^{-1}\left[\frac{\rho_{G1} \cos(\phi_{2PT} + \alpha_{P1}) + b_1 \sin\beta_1 + f_{P1} \sin(\phi_{2PT} + \alpha_{P1})}{a_{G1}}\right] + \delta_{G1} \quad \text{(F-30)}$$

Sensing Equations for the Determination of Contact of Subsequent Tooth Mesh

Contact will occur as soon as

$$\sqrt{L_{x1}^2 + L_{y1}^2} \leq \rho_{G1} + \rho_{P1} \quad \text{(F-31)}$$

where

$$L_{x1} = b_1 \cos\beta_1 + a_{P1} \cos(\phi_{2P} + \Delta\phi_{2P} - \delta_{P1}) - a_{G1} \cos(\phi_1 - \Delta\phi_1 - \delta_{G1}) \quad \text{(F-32)}$$

and

$$L_{y1} = b_1 \sin\beta_1 + a_{P1} \sin(\phi_{2P} + \Delta\phi_{2P} - \delta_{P1}) - a_{G1} \sin(\phi_1 - \Delta\phi_1 - \delta_{G1}) \quad \text{(F-33)}$$

The above requires the substitution of positive values for $\Delta\phi_{2P}$ and $\Delta\phi_1$, the tooth spacing angles.

Further, as in references 1 and 2, the angle ϕ_{2P} must be determined for the round-on-flat phase of motion, since the initial contact of the subsequent set of meshing teeth is preceded by this phase of motion. This means that equation F-14 is applicable.

FORWARD KINEMATICS OF MESH NO. 2

(Angle ϕ_{2G} is input, angle ϕ_S is output)

Round-on-Round Phase of Motion (fig. F-3)

Angle ϕ_S

$$\phi_S = 2 \tan^{-1} \frac{A_{2R} \pm \sqrt{A_{2R}^2 + B_{2R}^2 - C_{2R}^2}}{B_{2R} + C_{2R}} \tag{F-34}$$

with appropriate choice of sign, and

$$A_{2R} = a_{G2} \sin (\phi_{2G} + \delta_{G2} - \delta_{P2}) - b_2 \sin (\beta_2 - \delta_{P2}) \tag{F-35}$$

$$B_{2R} = a_{G2} \cos (\phi_{2G} + \delta_{G2} - \delta_{P2}) - b_2 \cos (\beta_2 - \delta_{P2}) \tag{F-36}$$

$$C_{2R} = \frac{a_{P2}^2 + a_{G2}^2 + b_2^2 - L_2^2 - 2a_{G2}\, b_2 \cos (\phi_{2G} + \delta_{G2} - \beta_2)}{2a_{P2}} \tag{F-37}$$

Angle λ_2

$$\lambda_2 = \cos^{-1}\left[\frac{b_2 \cos \beta_2 + a_{P2} \cos (\phi_S + \delta_{P2}) - a_{G2} \cos (\phi_{2G} + \delta_{G2})}{L_2}\right] \tag{F-38}$$

$$\lambda_2 = \sin^{-1}\left[\frac{b_2 \sin \beta_2 + a_{P2} \sin (\phi_S + \delta_{P2}) - a_{G2} \sin (\phi_{2G} + \delta_{G2})}{L_2}\right] \tag{F-39}$$

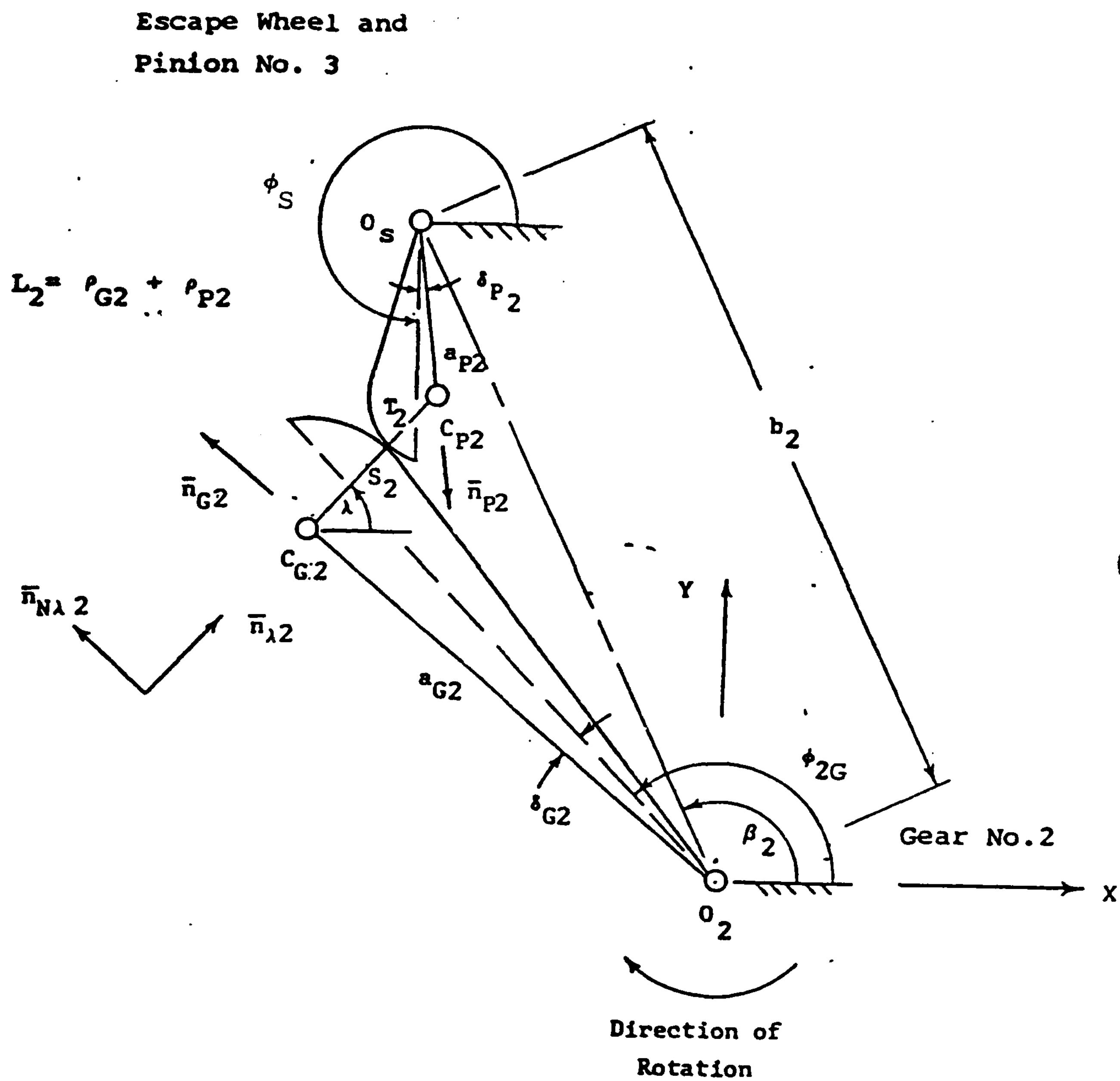


Figure F-3. Round-on-round phase of motion for mesh no. 2

Output Angular Velocity $\dot{\phi}$[3] of Escape Wheel

$$\dot{\phi} = \dot{\phi}_{2G} \frac{L_{2R}}{M_{2R}} \tag{F-40}$$

where

$$L_{2R} = B_{2RD} \cos \phi_S - A_{2RD} \sin \phi_S + C_{2RD} \tag{F-41}$$

$$M_{2R} = A_{2R} \cos \phi_S - B_{2R} \sin \phi_S \tag{F-42}$$

and

$$A_{2RD} = a_{G2} \cos (\phi_{2G} + \delta_{G2} - \delta_{P2}) \tag{F-43}$$

$$B_{2RD} = a_{G2} \sin (\phi_{2G} + \delta_{G2} - \delta_{P2}) \tag{F-44}$$

$$C_{2RD} = \frac{a_{G2}\, b_2 \sin (\phi_{2G} + \delta_{G2} - \beta_2)}{a_{P2}} \tag{F-45}$$

Note that in equation F-40

$$\dot{\phi}_{2G} = \dot{\phi}_{2P} = \dot{\phi}_2 \tag{F-46}$$

Relative Velocity $\overline{V}_{S2/T2_R}$ at the Contact Point

$$\overline{V}_{S2/T2_R} = \left\{\dot{\phi}_{2G}\left[a_{G2}\cos\left(\phi_{2G} + \delta_{G2} - \lambda_2\right) + \rho_{G2}\right]\right. \\ \left. -\dot{\phi}[a_{P2} \cos (\phi_S + \delta_{P2} - \lambda_2) - \rho_{P2}]\right\}\overline{n}_{N\lambda 2} \tag{F-47}$$

Round-on-Flat Phase of Motion (fig. F-4)

Angle ϕ_S

$$\phi_s = 2 \tan^{-1} \frac{A_{2F} \pm \sqrt{A_{2F}^2 + B_{2F}^2 - C_{2F}^2}}{B_{2F} + C_{2F}} \tag{F-48}$$

---

[3]The notation $\dot{\phi}$ is identical with $\dot{\phi}_S$. It is used, since the derivations in appendix D show this form of the escape wheel angular velocity.

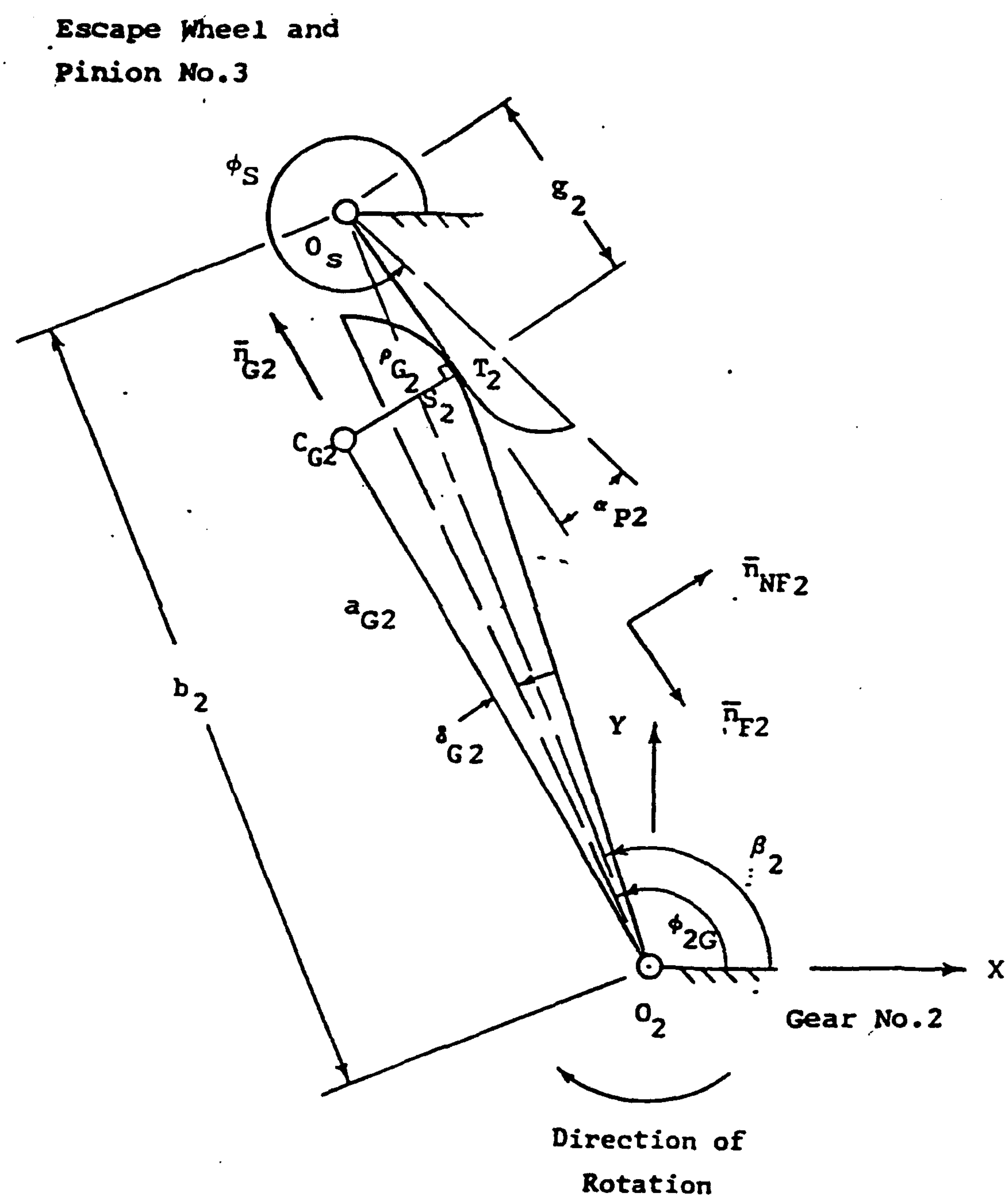


Figure F-4. Round-on-flat phase of motion for mesh no. 2

with appropriate choice of sign, and

$$A_{2F} = a_{G2} \cos(\phi_{2G} + \delta_{G2} + \alpha_{P2}) - b_2 \cos(\beta_2 + \alpha_{P2}) \tag{F-49}$$

$$B_{2F} = -a_{G2} \sin(\phi_{2G} + \delta_{G2} + \alpha_{P2}) + b_2 \sin(\beta_2 + \alpha_{P2}) \tag{F-50}$$

$$C_{2F} = \rho_{G2} \tag{F-51}$$

Distance g_2

$$g_2 = \frac{a_{G2} \sin(\phi_{2G} + \delta_{G2}) + \rho_{G2} \cos(\phi_S - \alpha_{P2}) - b_2 \sin \beta_2}{\sin(\phi_S - \alpha_{P2})} \tag{F-52}$$

Output Angular Velocity $\dot{\phi}$

$$\dot{\phi} = \dot{\phi}_{2G} \frac{L_{2F}}{M_{2F}} \tag{F-53}$$

where

$$L_{2F} = A_{2FD} \sin \phi_S + B_{2FD} \cos \phi_S \tag{F-54}$$

$$M_{2F} = A_{2F} \cos \phi_S - B_{2F} \sin \phi_S \tag{F-55}$$

and

$$A_{2FD} = a_{G2} \sin(\phi_{2G} + \delta_{G2} + \alpha_{P2}) \tag{F-56}$$

$$B_{2FD} = a_{G2} \cos(\phi_{2G} + \delta_{G2} + \alpha_{P2}) \tag{F-57}$$

Equation F-46 is also applicable to equation F-53.

Relative Velocity $\bar{V}_{S2/T2_F}$ at Contact Point

$$\bar{V}_{S2/T2_F} = \dot{\phi}_2 \left[a_{G2} \sin(\phi_S - \alpha_{P2} - \phi_{2G} - \delta_{G2}) - \rho_{G2}\right] \bar{n}_{F2} \tag{F-58}$$

Transition Angles ϕ_{ST} and ϕ_{2GT}

$$\phi_{ST} = 2 \tan^{-1} \frac{A_{2T} \pm \sqrt{A_{2T}^2 + B_{2T}^2 - C_{2T}^2}}{B_{2T} + C_{2T}} \tag{F-59}$$

with appropriate choice of sign, and

$$A_{2T} = \rho_{G2} \cos(\beta_2 + \alpha_{P2}) + f_{P2} \sin(\beta_2 + \alpha_{P2}) \tag{F-60}$$

$$B_{2T} = -\rho_{G2} \sin(\beta_2 + \alpha_{P2}) + f_{P2} \cos(\beta_2 + \alpha_{P2}) \tag{F-61}$$

$$C_{2T} = \frac{a_{G2}^2 - \rho_{G2}^2 - b_2^2 - f_{P2}^2}{2b_2} \tag{F-62}$$

$$\phi_{2GT} = \cos^{-1}\left[\frac{\rho_{G2} \sin(\phi_{ST} - \alpha_{P2}) + f_{P2} \cos(\phi_{ST} - \alpha_{P2}) + b_2 \cos\beta_2}{a_{G2}}\right] - \delta_{G2} \tag{F-63}$$

$$\phi_{2GT} = \sin^{-1}\left[\frac{-\rho_{G2} \cos(\phi_{ST} - \alpha_{P2}) + f_{P2} \sin(\phi_{ST} - \alpha_{P2}) + b_2 \sin\beta_2}{a_{G2}}\right] - \delta_{G2} \tag{F-64}$$

Sensing Equations for the Determination of Contact of Subsequent Tooth Mesh

Contact will occur as soon as

$$\sqrt{L_{x2}^2 + L_{y2}^2} \leq \rho_{G2} + \rho_{P2} \tag{F-65}$$

where

$$L_{x2} = b_2 \cos\beta_2 + a_{P2} \cos(\phi_S - \Delta\phi_S + \delta_{P2}) - a_{G2} \cos(\phi_{2G} + \Delta\phi_{2G} + \delta_{G2}) \tag{F-66}$$

$$L_{y2} = b_2 \sin\beta_2 + a_{P2} \sin(\phi_S - \Delta\phi_S + \delta_{P2}) - a_{G2} \sin(\phi_{2G} + \Delta\phi_{2G} + \delta_{G2}) \tag{F-67}$$

The above requires the substitution of positive values for $\Delta\phi_S$ and $\Delta\phi_{2G}$, the tooth spacing angles. The angle ϕ_S must be found according to equation F-48.

REVERSE KINEMATICS OF MESH NO. 1

(Angle ϕ_{2P} is input and angle ϕ_1 is output)

Round-on-Round Phase of Motion (fig. F-1)

Angle ϕ_1

$$\phi_1 = 2 \tan^{-1} \frac{D_{1R} \pm \sqrt{D_{1R}^2 + E_{1R}^2 - F_{1R}^2}}{E_{1R} + F_{1F}} \tag{F-68}$$

with appropriate choice of sign, and

$$D_{1R} = -2a_{G1}\left[a_{P1} \sin\left(\phi_{2P} + \delta_{G1} - \delta_{P1}\right) + b_1 \sin\left(\beta_1 + \delta_{G1}\right)\right] \tag{F-69}$$

$$E_{1R} = -2a_{G1}\left[a_{P1} \cos\left(\phi_{2P} + \delta_{G1} - \delta_{P1}\right) + b_1 \cos\left(\beta_1 + \delta_{G1}\right)\right] \tag{F-70}$$

$$F_{1R} = L_1^2 - a_{G1}^2 - a_{P1}^2 - b_1^2 - 2a_{P1}\, b_1 \cos\left(\phi_{2P} - \beta_1 - \delta_{P1}\right) \tag{F-71}$$

Angular Velocity $\dot{\phi}_1$

$$\dot{\phi}_1 = \dot{\phi}_{2P}\, \mathrm{DER1R} \tag{F-72}$$

where

$$\mathrm{DER1R} = \frac{F_{1RD} - D_{1RD} \sin \phi_1 - E_{1RD} \cos \phi_1}{D_{1R} \cos \phi_1 - E_{1R} \sin \phi_1} \tag{F-73}$$

and

$$D_{1RD} = -\,2a_{G1}\, a_{P1} \cos\left(\phi_{2P} + \delta_{G1} - \delta_{P1}\right) \tag{F-74}$$

$$E_{1RD} = 2a_{G1}\, a_{P1} \sin\left(\phi_{2P} + \delta_{G1} - \delta_{P1}\right) \tag{F-75}$$

$$F_{1RD} = 2a_{P1}\, b_1 \sin\left(\phi_{2P} - \beta_1 - \delta_{P1}\right) \tag{F-76}$$

Angular Acceleration $\ddot{\phi}_1$

$$\ddot{\phi}_1 = \ddot{\phi}_{2P} Y_1 + \dot{\phi}_{2P}^2 Y_2 \tag{F-77}$$

where

$$Y_1 = X_1 X_2 \tag{F-78}$$

$$Y_2 = X_1 X_3 \tag{F-79}$$

and

$$X_1 = \frac{1}{D_{1R} \cos \phi_1 - E_{1R} \sin \phi_1} \tag{F-80}$$

$$X_2 = F_{1RD} - D_{1RD} \sin \phi_1 - E_{1RD} \cos \phi_1 \tag{F-81}$$

$$\begin{aligned} X_3 = {} & F_{1RD} - D_{1RDD} \sin \phi_1 - E_{1RDD} \cos \phi_1 \\ & + \mathrm{DER1R} \left[2 E_{1RD} \sin \phi_1 - 2 D_{1RD} \cos \phi_1\right] \\ & + \mathrm{DER1R}^2 \left[D_{1R} \sin \phi_1 + E_{1R} \cos \phi_1\right] \end{aligned} \tag{F-82}$$

with

$$D_{1RDD} = 2a_{G1} \, a_{P1} \sin (\phi_{2P} + \delta_{G1} - \delta_{P1}) \tag{F-83}$$

$$E_{1RDD} = 2a_{G1} \, a_{P1} \cos (\phi_{2P} + \delta_{G1} - \delta_{P1}) \tag{F-84}$$

$$F_{1RDD} = 2a_{P1} \, b_1 \cos (\phi_{2P} - \beta_1 - \delta_{P1}) \tag{F-85}$$

Round-on-Flat Phase of Motion (fig. F-2)

Angle ϕ_1

$$\phi_1 = 2 \tan^{-1} \frac{D_{1F} \pm \sqrt{D_{1F}^2 + E_{1F}^2 - F_{1F}^2}}{E_{1F} + F_{1F}} \tag{F-86}$$

with appropriate choice of sign, and

$$D_{1F} = - a_{G1} \cos (\phi_{2P} + \alpha_{P1} + \delta_{G1}) \tag{F-87}$$

$$E_{1F} = a_{G1} \sin (\phi_{2P} + \alpha_{P1} + \delta_{G1}) \tag{F-88}$$

$$F_{1F} = - \rho_{G1} + b_1 \sin (\phi_{2P} + \alpha_{P1} - \beta_1) \tag{F-89}$$

Angular Velocity $\dot{\phi}_1$

$$\dot{\phi}_1 = \dot{\phi}_{2P}\,\text{DER1F} \tag{F-90}$$

where

$$\text{DER1F} = \frac{F_{1FD} - D_{1FD}\sin\phi_1 - E_{1FD}\cos\phi_1}{D_{1F}\cos\phi_1 - E_{1F}\sin\phi_1} \tag{F-91}$$

and

$$D_{1FD} = a_{G1}\sin(\phi_{2P} + \alpha_{P1} + \delta_{G1}) \tag{F-92}$$

$$E_{1FD} = a_{G1}\sin(\phi_{2P} + \alpha_{P1} + \delta_{G1}) \tag{F-93}$$

$$F_{1FD} = b_1\cos(\phi_{2P} + \alpha_{P1} - \beta_1) \tag{F-94}$$

Angular Acceleration $\ddot{\phi}_1$

$$\ddot{\phi}_1 = \ddot{\phi}_{2P}Y_3 + \dot{\phi}_{2P}^2 Y_4 \tag{F-95}$$

where

$$Y_3 = X_4X_5 \tag{F-96}$$

$$Y_4 = X_4X_6 \tag{F-97}$$

and

$$X_4 = \frac{1}{(D_{1F}\cos\phi_1 - E_{1F}\sin\phi_1)} \tag{F-98}$$

$$X_5 = F_{1FD} - D_{1FD}\sin\phi_1 - E_{1FD}\cos\phi_1 \tag{F-99}$$

$$\begin{aligned} X_6 = {} & F_{1FDD} - D_{1FDD}\sin\phi_1 - E_{1FDD}\cos\phi_1 \\ & + \text{DER1F}\,[- 2\,D_{1FD}\cos\phi_1 + 2\,E_{1FD}\sin\phi_1] \\ & + \text{DER1F}^2[D_{1F}\sin\phi_1 + E_{1F}\cos\phi_1] \end{aligned} \tag{F-100}$$

and

$$D_{1FDD} = a_{G1} \cos(\phi_{2P} + \alpha_{P1} + \delta_{G1}) \tag{F-101}$$

$$E_{1FDD} = -a_{G1} \sin(\phi_{2P} + \alpha_{P1} + \delta_{G1}) \tag{F-102}$$

$$F_{1FDD} = -b_1 \sin(\phi_{2P} + \alpha_{P1} - \beta_1) \tag{F-103}$$

REVERSE KINEMATICS OF MESH NO. 2

(Angle ϕ_S is input and angle ϕ_{2G} is output)

Round-on-Round Phase of Motion (fig. F-3)

Angle ϕ_{2G}

$$\phi_{2G} = 2 \tan^{-1} \frac{D_{2R} \pm \sqrt{D_{2R}^2 + E_{2R}^2 - F_{2R}^2}}{E_{2R} + F_{2R}} \tag{F-104}$$

with appropriate choice of sign, and

$$D_{2R} = -2\, a_{P2}\, a_{G2} \sin(\phi_S + \delta_{P2} - \delta_{G2}) - 2\, a_{G2}\, b_2 \sin(\beta_2 - \delta_{G2}) \tag{F-105}$$

$$E_{2R} = -2\, a_{P2}\, a_{G2} \cos(\phi_S + \delta_{P2} - \delta_{G2}) - 2\, a_{G2}\, b_2 \cos(\beta_2 - \delta_{G2}) \tag{F-106}$$

$$F_{2R} = L_2^2 - a_{G2}^2 - a_{P2}^2 - b_2^2 - 2\, a_{P2}\, b_2 \cos(\phi_S + \delta_{P2} - \beta_2) \tag{F-107}$$

Angular Velocity $\dot{\phi}_{2G}$

$$\dot{\phi}_{2G} = \dot{\phi}\ \mathrm{DER2R} \tag{F-108}$$

where

$$\mathrm{DER2R} = \frac{F_{2RD} - D_{2RD} \sin\phi_{2G} - E_{2RD} \cos\phi_{2G}}{D_{2R} \cos\phi_{2G} - E_{2R} \sin\phi_{2G}} \tag{F-109}$$

and

$$D_{2RD} = -2\, a_{P2}\, a_{G2} \cos(\phi_S + \delta_{P2} - \delta_{G2}) \tag{F-110}$$

$$E_{2RD} = 2\, a_{P2}\, a_{G2} \sin(\phi_S + \delta_{P2} - \delta_{G2}) \tag{F-111}$$

$$F_{2RD} = 2\, a_{P2}\, b_2 \sin(\phi_S + \delta_{P2} - \beta_2) \qquad \text{(F-112)}$$

Angular Acceleration $\ddot{\phi}_{2G}$

$$\ddot{\phi}_{2G} = \ddot{\phi} Y_5 + \dot{\phi}^2 Y_6 \qquad \text{(F-113)}$$

where

$$Y_5 = X_7 X_8 \qquad \text{(F-114)}$$

$$Y_6 = X_7 X_9 \qquad \text{(F-115)}$$

and

$$X_7 = \frac{1}{D_{2R} \cos\phi_{2G} - E_{2R} \sin\phi_{2G}} \qquad \text{(F-116)}$$

$$X_8 = F_{2RD} - D_{2RD} \sin\phi_{2G} - E_{2RD} \cos\phi_{2G} \qquad \text{(F-117)}$$

$$\begin{aligned} X_9 = {} & F_{2RDD} - D_{2RDD} \sin\phi_{2G} - E_{2RDD} \cos\phi_{2G} \\ & + \mathrm{DER2R}\, [-2\, D_{2RD} \cos\phi_{2G} + 2\, E_{2RD} \sin\phi_{2G}] \\ & + \mathrm{DER2R}^2\, [D_{2R} \sin\phi_{2G} + E_{2R} \cos\phi_{2G}] \end{aligned} \qquad \text{(F-118)}$$

$$D_{2RDD} = 2\, a_{P2}\, a_{G2} \sin(\phi_S + \delta_{P2} - \delta_{G2}) \qquad \text{(F-119)}$$

$$E_{2RDD} = 2\, a_{P2}\, a_{G2} \cos(\phi_S + \delta_{P2} - \delta_{G2}) \qquad \text{(F-120)}$$

$$F_{2RDD} = 2\, a_{P2}\, b_2 \cos(\phi_S + \delta_{P2} - \beta_2) \qquad \text{(F-121)}$$

Round-on-Flat Phase of Motion (fig. F-4)

Angle ϕ_{2G}

$$\phi_{2G} = 2 \tan^{-1} \frac{D_{2F} \pm \sqrt{D_{2F}^2 + E_{2F}^2 - F_{2F}^2}}{E_{2F} + F_{2F}} \qquad \text{(F-122)}$$

with appropriate choice of sign, and

$$D_{2F} = - a_{G2} \cos (\phi_S - \alpha_{P2} - \delta_{G2}) \tag{F-123}$$

$$E_{2F} = a_{G2} \sin (\phi_S - \alpha_{P2} - \delta_{G2}) \tag{F-124}$$

$$F_{2F} = \rho_{G2} + b_2 \sin (\phi_S - \alpha_{P2} - \beta_2) \tag{F-125}$$

Angular Velocity $\dot{\phi}_2$

$$\dot{\phi}_{2G} = \dot{\phi}\ \mathrm{DER2F} \tag{F-126}$$

where

$$\mathrm{DER2F} = \frac{F_{2FD} - D_{2FD} \sin \phi_{2G} - E_{2FD} \cos \phi_{2G}}{D_{2F} \cos \phi_{2G} - E_{2F} \sin \phi_{2G}} \tag{F-127}$$

and

$$D_{2FD} = a_{G2} \sin (\phi_S - \alpha_{P2} - \delta_{G2}) \tag{F-128}$$

$$E_{2FD} = a_{G2} \cos (\phi_S - \alpha_{P2} - \delta_{G2}) \tag{F-129}$$

$$F_{2FD} = b_2 \cos (\phi_S - \alpha_{P2} - \beta_2) \tag{F-130}$$

Angular Acceleration $\ddot{\phi}_2$

$$\ddot{\phi}_{2G} = \ddot{\phi} Y_7 + \dot{\phi}^2 Y_8 \tag{F-131}$$

where

$$Y_7 = X_{10} X_{11} \tag{F-132}$$

$$Y_8 = X_{10} X_{12} \tag{F-133}$$

and

$$X_{10} = \frac{1}{D_{2F} \cos \phi_{2G} - E_{2F} \sin \phi_{2G}} \tag{F-134}$$

$$X_{11} = F_{2FD} - D_{2FD} \sin \phi_{2G} - E_{2FD} \cos \phi_{2G} \tag{F-135}$$

$$X_{12} = F_{2FDD} - D_{2FDD} \sin \phi_{2G} - E_{2FDD} \cos \phi_{2G}$$

$$+ DER2F \left[-2D_{2FD} \cos \phi_{2G} + 2E_{2FD} \sin \phi_{2G}\right]$$

$$+ DER2F^2 \left[D_{2F} \sin \phi_{2G} + E_{2F} \cos \phi_{2G}\right] \tag{F-136}$$

and

$$D_{2FDD} = a_{G2} \cos (\phi_S - \alpha_{P2} - \delta_{G2}) \tag{F-137}$$

$$E_{2FDD} = -a_{G2} \sin \left(\phi_S - \alpha_{P2} - \delta_{G2}\right) \tag{F-138}$$

$$F_{2FDD} = -b_2 \sin (\phi_S - \alpha_{P2} - \beta_2) \tag{F-139}$$

ANGULAR VELOCITIES AND ACCELERATIONS OF GEAR AND PINION NO. 2 AND ROTOR GEAR NO. 1 IN TERMS OF THE ESCAPE WHEEL ANGULAR VELOCITY $\dot{\phi}$ AND ANGULAR ACCELERATION $\ddot{\phi}$ FOR VARIOUS MESH CONTACT MODES

Case No. 1: RR (Mesh 2: Round-on-Round; Mesh 1: Round-on-Round)

According to equations F-72 and F-77, the angular velocity and acceleration of the rotor gear of mesh 1 in the round-on-round phase are given, respectively by

$$\dot{\phi}_1 = \dot{\phi}_{2P}\, DER1R \tag{F-72}$$

$$\ddot{\phi}_1 = \ddot{\phi}_{2P} Y_1 + \dot{\phi}_{2P}^2 Y_2 \tag{F-77}$$

According to equations F-108 and F-113, the angular velocity and acceleration of gear no. 2 of mesh 2 in the round-on-round phase is given by

$$\dot{\phi}_{2G} = \dot{\phi} DER2R \tag{F-108}$$

$$\ddot{\phi}_{2G} = \ddot{\phi} Y_5 + \dot{\phi}^2 Y_6 \tag{F-113}$$

Since

$$\dot{\phi}_{2P} = \dot{\phi}_{2G} = \dot{\phi}_2 \tag{F-140}$$

and

$$\ddot{\phi}_{2P} = \ddot{\phi}_{2G} = \ddot{\phi}_2. \tag{F-141}$$

the angular velocity $\dot{\phi}_1$ of the rotor gear 1 becomes

$$\dot{\phi}_1 = \dot{\phi}(\text{DER1R})\ (\text{DER2R}) \tag{F-142}$$

The angular acceleration $\ddot{\phi}_1$ of the rotor is also obtained by appropriate substitution, i.e.,

$$\ddot{\phi}_1 = \ddot{\phi}[Y_1 Y_5] + \dot{\phi}^2[Y_1 Y_6 + Y_2(\text{DER2R})^2] \tag{F-143}$$

Case No. 2: RF (Mesh 2: Round-on-Round; Mesh 1: Round-on-Flat)

According to equations F-90 and F-95, the angular velocity and acceleration of the rotor gear of mesh 1 in the round-on-flat phase are given, respectively, by

$$\dot{\phi}_1 = \dot{\phi}_{2P}\ \text{DER1F} \tag{F-90}$$

$$\ddot{\phi}_1 = \ddot{\phi}_{2P} Y_3 + \dot{\phi}_{2P}^2 Y_4 \tag{F-95}$$

Equations F-117 and F-122 are again used to describe the angular velocity and acceleration of gear and pinion no. 2 of mesh 2 in the round-on-round phase. Since, again

$$\dot{\phi}_{2P} = \dot{\phi}_{2G} \tag{F-144}$$

and

$$\ddot{\phi}_{2P} = \ddot{\phi}_{2G}, \tag{F-145}$$

the angular velocity $\dot{\phi}_1$ of the rotor gear 1 becomes on substitution of equation F-108 into equation F-90

$$\dot{\phi}_1 = \dot{\phi}(\text{DER1F})\ (\text{DER2R}) \tag{F-146}$$

Appropriate substitution of equation F-113 into equation F-95, yields for the angular acceleration $\ddot{\phi}_1$ of the rotor gear 1 the following

$$\ddot{\phi}_1 = \ddot{\phi}[Y_3Y_5] + \dot{\phi}^2[Y_3Y_6 + Y_4(DER2R)^2] \quad \text{(F-147)}$$

Case No. 3: FF (Mesh 2: Round-on-Flat; Mesh 1: Round-on-Flat)

As for case 2, equations F-90 and F-95 give the velocity and acceleration relationships for mesh 1 in the round-on-flat phase.

Equations F-126 and F-131 give the angular velocity and acceleration of gear and pinion no. 2 of mesh 2 in the round-on-flat phase as follows:

$$\dot{\phi}_{2G} = \dot{\phi}DER2F \quad \text{(F-126)}$$

and

$$\ddot{\phi}_{2G} = \ddot{\phi}Y_7 + \dot{\phi}^2Y_8 \quad \text{(F-131)}$$

Again

$$\dot{\phi}_{2P} = \dot{\phi}_{2G} \quad \text{(F-148)}$$

and

$$\ddot{\phi}_{2P} = \ddot{\phi}_{2G} \quad \text{(F-149)}$$

Appropriate substitution of equation F-126 into F-90 furnishes the angular velocity $\dot{\phi}_1$ of the rotor gear 1 in terms of the escape wheel angular velocity $\dot{\phi}$ for the present FF case

$$\dot{\phi}_1 = \dot{\phi}(DER1F)\ (DER2F) \quad \text{(F-150)}$$

Similar substitution of equation F-131 into equation F-95 furnishes the angular acceleration $\ddot{\phi}_1$ of the rotor gear

$$\ddot{\phi}_1 = \ddot{\phi}[Y_3Y_7] + \dot{\phi}^2[Y_3Y_8 + Y_4(DER2F)^2] \quad \text{(F-151)}$$

Case No. 4: FR (Mesh 2: Round-on-Flat; Mesh 2: Round-on-Round)

To obtain the angular velocity $\dot{\phi}_1$ equation F-126 is substituted into equation F-72. In a similar procedure, the angular acceleration $\ddot{\phi}_1$ results from the substitution of equation F-131 into equation F-77. In either case, the following equalities must be observed:

$$\dot{\phi}_{2P} = \dot{\phi}_{2G} \tag{F-152}$$

and

$$\ddot{\phi}_{2P} = \ddot{\phi}_{2G} \tag{F-153}$$

Then,

$$\dot{\phi}_1 = \dot{\phi}(DER1R)(DER2F) \tag{F-154}$$

and

$$\ddot{\phi}_1 = \ddot{\phi}[Y_1Y_7] + \dot{\phi}^2[Y_1Y_8 + Y_2(DER2F)^2] \tag{F-155}$$

REFERENCES

1. Lowen, G. G. and Tepper, F. R., "Fuze Gear Train Analysis," Technical Report ARLCD-TR-79030, ARRADCOM, Dover, NJ, December 1979.

2. Lowen, G. G. and Tepper, F. R., "Fuze Gear Train Efficiency," Technical Report ARLCD-TR-80024, ARRADCOM, Dover, NJ, November 1981.

APPENDIX G

PROJECTILE KINEMATICS IN TERMS OF COORDINATE SYSTEM FIXED TO UNDERSIDE OF MECHANISM PLANE (APPLICABLE TO M577 S&A)

The projectile in figure D-1 of appendix D, which shows the M577 S&A located on the underside of the mechanism plane, was rotated 180 degrees about the X_p axis, when compared to its original position in figure C-1 of appendix C. (Note that the relative position of the center of mass C_{PR} of the projectile remains undisturbed.

This rotation places the Y_p and Z_p axes in opposite directions to the Y and Z axes, respectively, of the newly introduced coordinate system which is attached to the under-side of the mechanism plane.

It is therefore necessary to express the aeroballistic kinematics of appendix A in terms of this new X-Y-Z system. Figure G-1, which represents a revision of figure A-1, is used for this purpose. The original lower case x-y-z system is now labeled X_p-Y_p-Z_p.

When the angular velocity components of the projectile are now expressed in this new system (with additional subscript u), one obtains:

$$\omega_{xu} = \dot{\theta}_E \cos \phi_E + \dot{\psi}_E \sin \theta_E \sin \phi_E \tag{G-1}$$

$$\omega_{yu} = \dot{\theta}_E \sin \phi_E - \dot{\psi}_E \sin \theta_E \cos \phi_E \tag{G-2}$$

$$\omega_{zu} = -\dot{\phi}_E - \dot{\psi}_E \cos \theta_E \tag{G-3}$$

Differentiation of the above expressions furnishes the components of the angular acceleration of the projectile in this system

$$\begin{aligned} \dot{\omega}_{xu} = {} & \ddot{\theta}_E \cos \phi_E - \dot{\theta}_E\dot{\phi}_E \sin \phi_E + \ddot{\psi}_E \sin \theta_E \sin \phi_E \\ & + \dot{\psi}_E\dot{\theta}_E \cos \theta_E \sin \phi_E + \dot{\psi}_E\dot{\phi}_E \sin \theta_E \cos \phi_E \end{aligned} \tag{G-4}$$

$$\begin{aligned} \dot{\omega}_{yu} = {} & \ddot{\theta}_E \sin \phi_E + \dot{\theta}_E\dot{\phi}_E \cos \phi_E - \ddot{\psi}_E \sin \theta_E \cos \phi_E \\ & - \dot{\psi}_E\dot{\theta}_E \cos \theta_E \cos \phi_E + \dot{\psi}_E\dot{\phi}_E \sin \theta_E \sin \phi_E \end{aligned} \tag{G-5}$$

$$\dot{\omega}_{zu} = -\ddot{\phi}_E - \ddot{\psi}_E \cos\theta_E + \dot{\psi}_E \dot{\theta}_E \sin\theta_E \tag{G-6}$$

Comparison with equations A-2 to A-4 and A-6 to A-8, respectively, shows that the changing requirements can be satisfied by the following general notation

$$\omega_{xGEN} = \omega_x \tag{G-7}$$

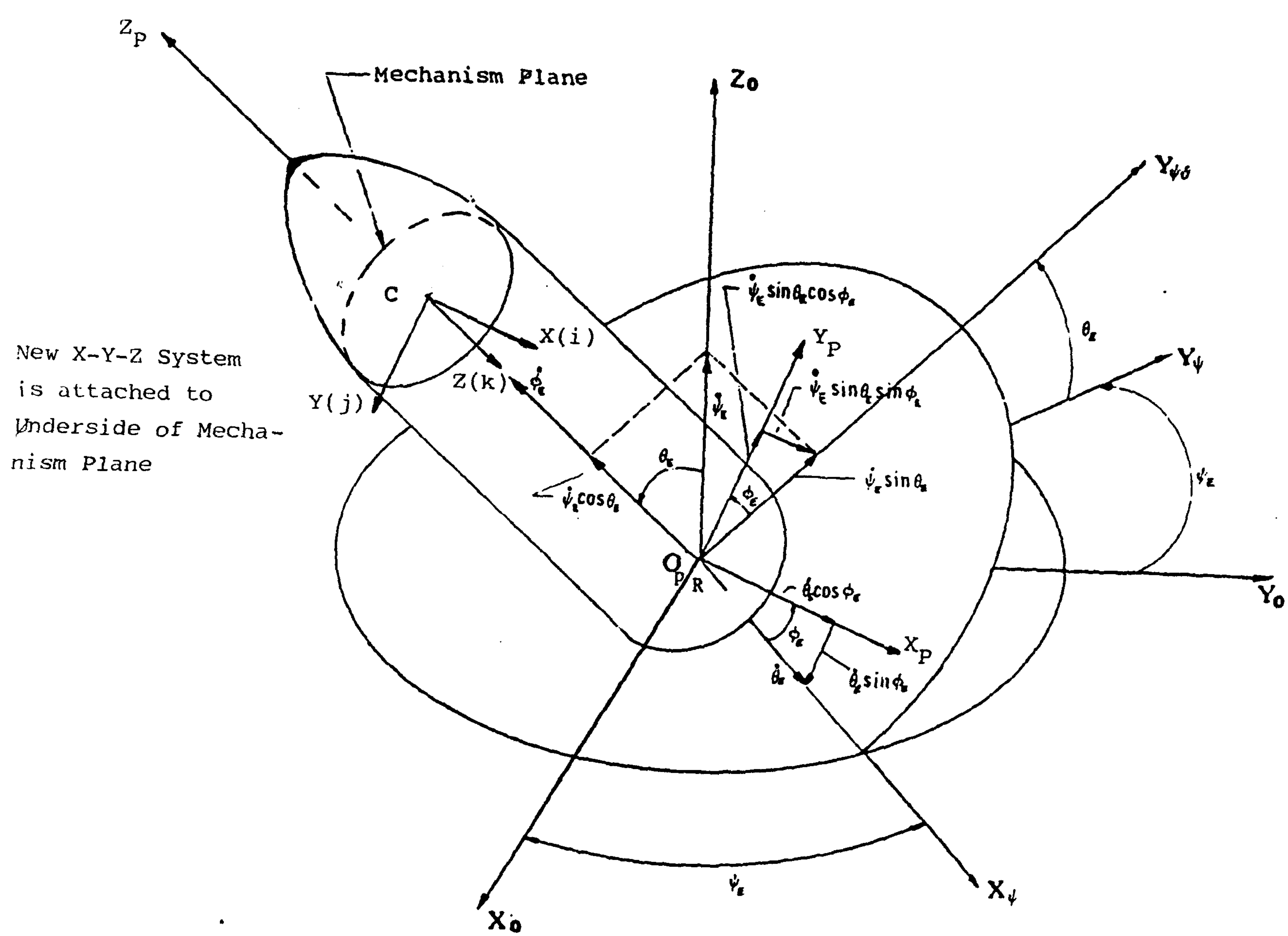


Figure G-1. Relationship of X-Y-Z coordinate system fixed to underside of mechanism plane to aeroballistic coordinate system

$$\omega_{yGEN} = s_8 \omega_y \tag{G-8}$$

$$\omega_{zGEN} = s_8 \omega_z \tag{G-9}$$

and

$$\dot{\omega}_{xGEN} = \dot{\omega}_x \tag{G-10}$$

$$\dot{\omega}_{yGEN} = s_8 \dot{\omega}_y \tag{G-11}$$

$$\dot{\omega}_{zGEN} = s_8 \dot{\omega}_z \tag{G-12}$$

In the above

$$s_8 = +1 \tag{G-13}$$

when equations A-2 to A-8 are applicable, and

$$s_8 = -1 \tag{G-14}$$

when equations G-1 to G-6 are needed.

In addition to the above, the sign of the drag deceleration (first used in equation E-14, ref 1 and given in appendix E of this report) must also be responsive to the location of the S&A with respect to the mechanism plane. Thus

$$\ddot{Z}_{GEN} = -s_8 \left| \ddot{Z} \right| \tag{G-15}$$

where $\left| \ddot{Z} \right|$ is the absolute value of the projectile drag deceleration. Further

$$s_8 = +1 \tag{G-16}$$

when the S&A is located as in figure C-1 of appendix C of this report, on top of the mechanism plane. When the S&A is located on the underside of the mechanism plane, as shown in figure D-1 of appendix D

$$s_8 = -1 \tag{G-17}$$

in equation G-15.

REFERENCES

1. Tepper, F. R. and Lowen, G. G., "Computer Simulation of Artillery Safing and Arming Mechanism in Aeroballistic Environment (Involute Gear Train and Straight-Sided Verge Runaway Escapement)," Technical Report ARLCD-TR-83050, ARDC, Dover, NJ, July 1984.

APPENDIX H

PROGRAM AERCLOC

```
      PROGRAM AERCLOC(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)           000170
      COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,   000180
     +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY, 000190
     +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2, 000200
     +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,     000210
     +GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,    000220
     +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,   000230
     +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,          000240
     +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2        000250
     +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2                             000260
     +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,        000270
     +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,                         000280
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F 000290
      COMMON /DATA/ RPM                                                000300
      COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8                       000305
      COMMON /ZETA/ PSI,TIME,DPSI,GP,PHICUTD                           000310
      COMMON/DATA5/LU,LL,MU,MU1                                        000320
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,           000330
     +PHI2P,PHI1,PHI2,GAM                                              000340
      COMMON/DATA7/DER2R,DER2F,DER1R,DER1F                             000350
      COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S     000360
      COMMON/DATA13/PHISI,PHISFF,PHIST,PH2PI,PH2PFF,PH2PT              000370
      COMMON/DATA12/X1,X2,X3,X4,X5,X6,X7,X8,X9,X10,X11,X12,Y1,Y2,Y3,Y4, 000380
     +Y5,Y6,Y7,Y8                                                      000390
      DIMENSION AUX(8,2), AUX2(8,4), PRMT(5), PHI(2), DPHI(2), X(4), DX(000400
     14)                                                               000410
      REAL M1,M2,M3,MP,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,IXS,IYS000420
     +,IZS,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,MU,MU1,LU,LL,LAMBDA,NG1,NG2,  000430
     +NP2,NP3,N,NT,LX1,LY1,LL1,LX2,LY2,LL2,L1,L2,J1,J2                 000440
      EXTERNAL FCT,OUTP,FCTF,OUTPF                                     000450
C                                                                      000460
C     READ IN AND WRITE DATA                                           000470
C                                                                      000480
      READ (5,27) A,B,C,ALPHEN,ALPHEX,NT,CONFIG                        000490
      WRITE (6,28) A,B,C,ALPHEN,ALPHEX,NT,CONFIG                       000500
      READ (5,29) EREST,LAMBDA,N                                       000510
      WRITE (6,30) EREST,LAMBDA,N                                      000520
      READ (5,35) NG1,NG2,NP2,NP3,CAPRP1,CAPRP2,RP2,RP3                000530
      WRITE (6,38) NG1,NG2,NP2,NP3,CAPRP1,CAPRP2,RP2,RP3               000540
      READ(5,36)CAPRO1,CAPRO2,RO2,RO3                                  000550
      WRITE(6,775)CAPRO1,CAPRO2,RO2,RO3                                000560
  775 FORMAT(6X,*CAPRO1 =*,F8.5,3X,*CAPRO2 =*,F8.5,3X,*RO2 =*,         000570
     +F8.5,3X,*RO3 =*,F8.5/)                                           000580
      READ (5,31) M1,M2,M3,MP                                          000590
      WRITE (6,32) M1,M2,M3,MP                                         000600
      READ (5,17) IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1                        000610
      WRITE (6,18) IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1                       000620
      READ (5,19) IX2,IY2,IZ2                                          000630
      WRITE (6,20) IX2,IY2,IZ2                                         000640
      READ (5,19) IXS,IYS,IZS                                          000650
      WRITE (6,21) IXS,IYS,IZS                                         000660
      READ (5,17) IXXP,IEEP,IZZP,IXEP,IZXP,IEZP                        000670
      WRITE (6,22) IXXP,IEEP,IZZP,IXEP,IZXP,IEZP                       000680
      READ (5,33) RC1,RCP,RHOP,RPM,PHI1RCD,PSICCD,PHID,PHICUTD,MU,MU1  000690
      WRITE (6,34) RC1,RCP,RHOP,RPM,PHI1RCD,PSICCD,PHID,PHICUTD,MU,MU1 000700
      READ (5,23) LU,LL                                                000710
      WRITE (6,24) LU,LL                                               000720
```

```
      READ (5,29) RHO1,RHO2,RHO3                                    000730
      WRITE (6,40) RHO1,RHO2,RHO3                                   000740
      READ (5,36) RHOF1,RHOF2,RHOF3,RHOF                            000750
      WRITE (6,25) RHOF1,RHOF2,RHOF3,RHOF                           000760
      READ(5,29)RHOP1,RHOG1,TCG1                                    000770
      WRITE(6,700)RHOP1,RHOG1,TCG1                                  000780
      READ(5,29)RHOP2,RHOG2,TCG2                                    000790
  700 FORMAT(6X,*RHOP1 =*,F8.4,3X,*RHOG1 =*,F8.4,3X,*TCG1 =*,F8.4)  000800
      WRITE(6,701)RHOP2,RHOG2,TCG2                                  000810
  701 FORMAT(6X,*RHOP2 =*,F8.4,3X,*RHOG2 =*,F8.4,3X,*TCG2 =*,F8.4)  000820
      READ (5,36) R1,R2,R3,R4                                       000830
      WRITE (6,39) R1,R2,R3,R4                                      000840
      CALL GEAR(CAPRP1,CAPRO1,RHOG1,TCG1,AG1,DELG1)                 000850
      CALL PINION(RP2,RO2,RHOP1,AP1,DELP1,ALPHP1,FP1)               000860
      WRITE(6,41)AG1,AP1,ALPHP1,DELP1,DELG1,RHOP1,RHOG1,FP1         000870
   41 FORMAT(6X,*AG1 =*,F6.4,3X,*AP1 =*,F6.4,3X,*ALPHP1 =*,         000880
     +F7.3,3X,*DELP1 =*,F7.3,3X,*DELG1 =*,F7.3//6X,*RHOP1 =*,       000890
     +F7.3,3X,*RHOG1 =*,F7.3,3X,*FP1 =*,F6.4/)                      000900
      CALL GEAR(CAPRP2,CAPRO2,RHOG2,TCG2,AG2,DELG2)                 000910
      CALL PINION(RP3,RO3,RHOP2,AP2,DELP2,ALPHP2,FP2)               000920
      WRITE(6,42)AG2,AP2,ALPHP2,DELP2,DELG2,RHOP2,RHOG2,FP2         000930
   42 FORMAT(6X,*AG2 =*,F6.4,3X,*AP2 =*,F6.4,3X,*ALPHP2 =*,         000940
     +F7.3,3X,*DELP2 =*,F7.3,3X,*DELG2 =*,F7.3//6X,*RHOP2 =*,       000950
     +F7.3,3X,*RHOG2 =*,F7.3,3X,*FP2 =*,F6.4/)                      000960
      READ (5,37) J1,J2                                             000970
      WRITE (6,43) J1,J2                                            000980
      READ (5,36) RX,RY,RZ,S8                                       000981
      WRITE (6,26) RX,RY,RZ,S8                                      001000
C                                                                   001010
C     INITIALIZATION OF PARAMETERS AND CONVERSION TO RADIANS        001020
C                                                                   001030
      TIME=0.                                                       001040
      PHITOT=0.                                                     001050
      PHIPR=PHID                                                    001060
      DDPHI=0                                                       001070
      DPSI2=0.                                                      001080
      F23RRMX=0                                                     001090
      F12RRMX=0                                                     001100
      F23RFMX=0                                                     001110
      F12RFMX=0                                                     001120
      F23FRMX=0                                                     001130
      F12FRMX=0                                                     001140
      F23FFMX=0                                                     001150
      F12FFMX=0                                                     001160
      T23RRMX=0                                                     001170
      T12RRMX=0                                                     001180
      T23RFMX=0                                                     001190
      T12RFMX=0                                                     001200
      T23FRMX=0                                                     001210
      T12FRMX=0                                                     001220
      T23FFMX=0                                                     001230
      T12FFMX=0                                                     001240
      PNMAX=0                                                       001250
      LAMDA1=0                                                      001260
      LAMDA2=0                                                      001270
      G1=0                                                          001280
      G2=0                                                          001290
```

```
              X1=0                                        001300
              X2=0                                        001310
              X3=0                                        001320
              X4=0                                        001330
              X5=0                                        001340
              X6=0                                        001350
              X7=0                                        001360
              X8=0                                        001370
              X9=0                                        001380
              X10=0                                       001390
              X11=0                                       001400
              X12=0                                       001410
              Y1=0                                        001420
              Y2=0                                        001430
              Y3=0                                        001440
              Y4=0                                        001450
              Y5=0                                        001460
              Y6=0                                        001470
              Y7=0                                        001480
              Y8=0                                        001490
              DER1R=0                                     001500
              DER2R=0                                     001510
              DER1F=0                                     001520
              DER2F=0                                     001530
              S1R=0                                       001540
              S1F=0                                       001550
              S2R=0                                       001560
              S2F=0                                       001570
              RY=S8*RY                                    001575
              RZ=S8*RZ                                    001576
              PI=3.14159                                  001580
              ZZ=PI/180.                                  001590
              OMEGA=RPM*2.*PI/60.                         001600
              OM2=OMEGA*OMEGA                             001610
              PHI1RC=PHI1RCD*ZZ                           001620
              PSICC=PSICCD*ZZ                             001630
              PSIC=PSICC                                  001640
              ALPHEN=ALPHEN*ZZ                            001650
              ALPHEX=ALPHEX*ZZ                            001660
              DELTA=360./N                                001670
              DPHI1=360.*ZZ/NG1                           001680
              DPHI2P=360.*ZZ/NP2                          001690
              DPHI2=360.*ZZ/NG2                           001700
              DPHIS=360.*ZZ/NP3                           001710
        C                                                 001720
        C     COMPUTATION OF MESH CURVATURE SUMMATION     001730
        C                                                 001740
              L1=RHOG1+RHOP1                              001750
              L2=RHOG2+RHOP2                              001760
        C                                                 001770
        C     COMPUTATION OF MESH CENTER DISTANCES        001780
        C                                                 001790
              B1=CAPRP1+RP2                               001800
              B2=CAPRP2+RP3                               001810
        C                                                 001820
        C     DETERMINATION OF SIGNUM FUNCTION S6         001830
        C                                                 001840
```

```
      IF (CONFIG.EQ.1.) S6=1.
      IF (CONFIG.EQ.2.) S6=-1.
C
C     COMPUTATION OF GAMMAS AND BETAS
C
      GAMMA2=S6*ACOS((R1*R1+R2*R2-(CAPRP1+RP2)**2)/(2.*R1*R2))
      GAMA3P=ACOS((R2*R2+R3*R3-(CAPRP2+RP3)**2)/(2.*R2*R3))
      GAMMA3=GAMMA2+S6*GAMA3P
      GAMA4P=ACOS((R3*R3+R4*R4-A*A)/(2.*R3*R4))
      GAMMA4=GAMMA3+S6*GAMA4P
      GAMMA2D=GAMMA2/ZZ
      GAMMA3D=GAMMA3/ZZ
      GAMMA4D=GAMMA4/ZZ
      DELTA2=ACOS(((CAPRP1+RP2)**2+R1*R1-R2*R2)/(2.*R1*(CAPRP1+RP2)))
      DELTA3=ACOS(((CAPRP2+RP3)**2+R2*R2-R3*R3)/(2.*R2*(CAPRP2+RP3)))
      DELTA4=ACOS((A*A+R3*R3-R4*R4)/(2.*A*R3))
      BETA1=PI-S6*DELTA2
      BETA2=GAMMA2+PI-S6*DELTA3
      BETA3=GAMMA3+PI-S6*DELTA4
      IF (CONFIG.EQ.1.) GAMAPP=DELTA4+GAMA4P
      IF (CONFIG.EQ.2.) GAMAPP=2.*PI-DELTA4-GAMA4P
      BETA1D=BETA1/ZZ
      BETA2D=BETA2/ZZ
      BETA3D=BETA3/ZZ
      WRITE (6,44) BETA1D,BETA2D,BETA3D,GAMMA2D,GAMMA3D,GAMMA4D
C
C     PRELIMINARY COMPUTATIONS FOR MESH 1
C
C     DETERMINATION OF TRANSITION ANGLES FOR MESH 1
C
      A1T=-RHOG1*COS(BETA1-ALPHP1)+FP1*SIN(BETA1-ALPHP1)
      B1T=RHOG1*SIN(BETA1-ALPHP1)+FP1*COS(BETA1-ALPHP1)
      C1T=(AG1**2-RHOG1**2-B1**2-FP1**2)/(2.*B1)
      ROOT1T=A1T**2+B1T**2-C1T**2
      Y1T1=A1T+SQRT(ROOT1T)
      Y1T2=A1T-SQRT(ROOT1T)
      X1T=B1T+C1T
      PH2PT1=2.*ATAN2(Y1T1,X1T)
      IF(PH2PT1.LT.O)PH2PT1=PH2PT1+2.*PI
      PH2PT2=2.*ATAN2(Y1T2,X1T)
      IF(PH2PT2.LT.O)PH2PT2=PH2PT2+2.*PI
      CALL TRANS1(RHOG1,ALPHP1,BETA1,FP1,AG1,B1,DELG1,ZZ,PH2PT1,PHI1T1,
     +G11)
      IF(G11.GT.FP1)GO TO 51
      PHI1T=PHI1T1
      PH2PT=PH2PT1
      GO TO 53
   51 CALL TRANS1(RHOG1,ALPHP1,BETA1,FP1,AG1,B1,DELG1,ZZ,PH2PT2,PHI1T2,
     +G12)
      IF(G12.LT.FP1)GO TO 52
      WRITE(6,75)
      STOP
   75 FORMAT(*OSOMETHING IS WRONG WITH MESH 1*)
   52 PHI1T=PHI1T2
      PH2PT=PH2PT2
   53 PHI1TD=PHI1T/ZZ
      PH2PTD=PH2PT/ZZ
```

```
      WRITE(6, 76)PHI1TD,PH2PTD
   76 FORMAT(6X,*PHI1TD =*,F7.3,5X,*PH2PTD =*,F7.3)
C
C      DETERMINATION OF CORRECT SIGN FOR FORWARD ROUND-ON-FLAT
C      REGIME OF MESH 1
C
      A1F=AG1*COS(PHI1T-DELG1-ALPHP1)-B1*COS(BETA1-ALPHP1)
      B1F=-AG1*SIN(PHI1T-DELG1-ALPHP1)+B1 *SIN(BETA1-ALPHP1)
      C1F=-RHOG1
      ROOT1F=A1F**2+B1F**2-C1F**2
      Y1F1=A1F+SQRT(ROOT1F)
      Y1F2=A1F-SQRT(ROOT1F)
      X1F=B1F+C1F
      PH2PF1=2.*ATAN2(Y1F1,X1F)
      PH2PF2=2.*ATAN2(Y1F2,X1F)
      IF(PH2PF1.LT.O)PH2PF1=PH2PF1+2.*PI
      IF(PH2PF2.LT.O)PH2PF2=PH2PF2+2.*PI
      IF(ABS(PH2PF1-PH2PT).LT.ABS(PH2PF2-PH2PT))GO TO 54
      SIGN1F=-1.
      GO TO 55
   54 SIGN1F=1.
C
C     LATEST AND EARLIEST POSSIBLE VALUES OF PHI1 AND PHI2P FOR MESH 1
C
   55 DO 56 I=1,2000
      PHID1=PHI1TD+(I-1.)/100.
      PHI1=PHID1*ZZ
      A1F=AG1*COS(PHI1-DELG1-ALPHP1)-B1*COS(BETA1-ALPHP1)
      B1F=-AG1*SIN(PHI1-DELG1-ALPHP1)+B1*SIN(BETA1-ALPHP1)
      C1F=-RHOG1
      ROOT1F=A1F**2+B1F**2-C1F**2
      Y1F=A1F+SIGN1F*SQRT(ROOT1F)
      X1F=B1F+C1F
      PH2PF=2.*ATAN2(Y1F,X1F)
      LX1=B1*COS(BETA1)+AP1*COS(PH2PF+DPHI2P-DELP1)-AG1*COS(PHI1-DPHI1-
     1DELG1)
      LY1=B1*SIN(BETA1)+AP1*SIN(PH2PF+DPHI2P-DELP1)-AG1*SIN(PHI1-DPHI1-
     1DELG1)
      LL1=SQRT(LX1**2+LY1**2)
      DELEL1=LL1-L1
      IF(DELEL1.LE.O)GO TO 57
   56 CONTINUE
   57 PHI1F=PHI1
      PH2PFF=PH2PF
      IF(PH2PFF-PH2PT.GT..001)PH2PFF=PH2PFF-2.*PI
      PHI1I=PHI1F-DPHI1
      PH2PI=PH2PFF+DPHI2P
      PHI1ID=PHI1I/ZZ
      PH2PID=PH2PI/ZZ
      PHI1FD=PHI1F/ZZ
      PH2PFD=PH2PFF/ZZ
      WRITE(6,77)PHI1ID,PH2PID,PHI1FD,PH2PFD
   77 FORMAT(6X,*PHI1ID =*,F7.3,5X,*PH2PID =*,F7.3,5X,*PHI1FD =*,
     +F7.3,5X,*PH2PFD =*,F7.3)
C
C     DETERMINATION OF CORRECT SIGN FOR FORWARD ROUND-ON-ROUND REGIME
C     OF MESH 1
```

```
      C
            A1R=B1*SIN(BETA1+DELP1)-AG1*SIN(PHI1I-DELG1+DELP1)
            B1R=B1*COS(BETA1+DELP1)-AG1*COS(PHI1I-DELG1+DELP1)
            C1R=(L1**2-B1**2-AG1**2-AP1**2+2.*AG1*B1*COS(PHI1I-DELG1-BETA1))/
           +(2.*AP1)
            ROOT1R=A1R**2+B1R**2-C1R**2
            Y1R1=A1R+SQRT(ROOT1R)
            Y1R2=A1R-SQRT(ROOT1R)
            X1R=B1R+C1R
            PH2PR1=2.*ATAN2(Y1R1,X1R)
            PH2PR2=2.*ATAN2(Y1R2,X1R)
            IF(PH2PR1.LT.O)PH2PR1=PH2PR1+2.*PI
            IF(PH2PR2.LT.O)PH2PR2=PH2PR2+2.*PI
            IF(ABS(PH2PI-PH2PR1).LT.ABS(PH2PI-PH2PR2))GO TO 58
            SIGN1R=-1.
            GO TO 59
         58 SIGN1R=1.
      C
      C     REVERSE KINEMATICS OF MESH 1
      C
      C     DETERMINATION OF CORRECT SIGN FOR REVERSE ROUND-ON-ROUND REGIME
      C     FOR MESH 1
      C
         59 D1R=-2.*AG1*(AP1*SIN(PH2PI+DELG1-DELP1)+B1*SIN(BETA1+DELG1))
            E1R=-2.*AG1*(AP1*COS(PH2PI+DELG1-DELP1)+B1*COS(BETA1+DELG1))
            F1R=L1**2-AG1**2-AP1**2-B1**2-2.*AP1*B1*COS(PH2PI-BETA1-DELP1)
            ROOT1R=D1R**2+E1R**2-F1R**2
            Y1R1=D1R+SQRT(ROOT1R)
            Y1R2=D1R-SQRT(ROOT1R)
            X1R=E1R+F1R
            PHI1R1=2.*ATAN2(Y1R1,X1R)
            PHI1R2=2.*ATAN2(Y1R2,X1R)
            IF(PHI1R1.LT.O)PHI1R1=PHI1R1+2.*PI
            IF(PHI1R2.LT.O)PHI1R2=PHI1R2+2.*PI
            IF(ABS(PHI1I-PHI1R1).LT.ABS(PHI1I-PHI1R2)) GO TO 60
            RSGN1R=-1.
            GO TO 61
         60 RSGN1R=1.
      C
      C     DETERMINATION OF CORRECT SIGN FOR REVERSE ROUND-ON-FLAT REGIME
      C     FOR MESH 1
      C
         61 D1F=-AG1*COS(PH2PFF+ALPHP1+DELG1)
            E1F=AG1*SIN(PH2PFF+ALPHP1+DELG1)
            F1F=-RHOG1+B1*SIN(PH2PFF+ALPHP1-BETA1)
            ROOT1F=D1F**2+E1F**2-F1F**2
            Y1F1=D1F+SQRT(ROOT1F)
            Y1F2=D1F-SQRT(ROOT1F)
            X1F=E1F+F1F
            PHI1F1=2.*ATAN2(Y1F1,X1F)
            PHI1F2=2.*ATAN2(Y1F2,X1F)
            IF(PHI1F1.LT.O)PHI1F1=PHI1F1+2.*PI
            IF(PHI1F2.LT.O)PHI1F2=PHI1F2+2.*PI
            IF(ABS(PHI1F1-PHI1F).LT.ABS(PHI1F2-PHI1F))GO TO 62
            RSGN1F=-1.
            GO TO 63
         62 RSGN1F=1.
```

```
C
C     PRELIMINARY COMPUTATIONS FOR MESH 2
C
C     DETERMINATION OF TRANSITION ANGLES FOR MESH 2
C
   63 A2T=RHOG2*COS(BETA2+ALPHP2)+FP2*SIN(BETA2+ALPHP2)
      B2T=-RHOG2*SIN(BETA2+ALPHP2)+FP2*COS(BETA2+ALPHP2)
      C2T=(AG2**2-RHOG2**2-B2**2-FP2**2)/(2.*B2)
      ROOT2T=A2T**2+B2T**2-C2T**2
      Y2T1=A2T+SQRT(ROOT2T)
      Y2T2=A2T-SQRT(ROOT2T)
      X2T=B2T+C2T
      PHIST1=2.*ATAN2(Y2T1,X2T)
      PHIST2=2.*ATAN2(Y2T2,X2T)
      IF(PHIST1.LT.O)PHIST1=PHIST1+2.*PI
      IF(PHIST2.LT.O)PHIST2=PHIST2+2.*PI
      CALL TRANS2(RHOG2,ALPHP2,BETA2,FP2,AG2,B2,DELG2,ZZ,PHIST1,PHI2T1,
     +G21)
      IF(G21.GT.FP2)GO TO 64
      PHI2T=PHI2T1
      PHIST=PHIST1
      GO TO 66
   64 CALL TRANS2(RHOG2,ALPHP2,BETA2,FP2,AG2,B2,DELG2,ZZ,PHIST2,PHI2T2,
     +G22)
      IF(G22.LT.FP2)GO TO 65
      WRITE(6,72)
      STOP
   72 FORMAT(*OSOMETHING IS WRONG WITH MESH 2*)
   65 PHI2T=PHI2T2
      PHIST=PHIST2
   66 PHI2TD=PHI2T/ZZ
      PHISTD=PHIST/ZZ
      WRITE(6,73)PHI2TD,PHISTD
   73 FORMAT(6X,*PHI2TD =*,F7.3,5X,*PHISTD =*,F7.3)
C
C     DETERMINATION OF CORRECT SIGN FOR FORWARD ROUND-ON-FLAT REGIME
C     FOR MESH 2
C
      A2F=AG2*COS(PHI2T+DELG2+ALPHP2)-B2*COS(BETA2+ALPHP2)
      B2F=-AG2*SIN(PHI2T+DELG2+ALPHP2)+B2*SIN(BETA2+ALPHP2)
      C2F=RHOG2
      ROOT2F=A2F**2+B2F**2-C2F**2
      Y2F1=A2F+SQRT(ROOT2F)
      Y2F2=A2F-SQRT(ROOT2F)
      X2F=B2F+C2F
      PHISF1=2.*ATAN2(Y2F1,X2F)
      PHISF2=2.*ATAN2(Y2F2,X2F)
      IF(PHISF1.LT.O)PHISF1=PHISF1+2.*PI
      IF(PHISF2.LT.O)PHISF2=PHISF2+2.*PI
      IF(ABS(PHISF1-PHIST).LT.ABS(PHISF2-PHIST))GO TO 67
      SIGN2F=-1.
      GO TO 68
   67 SIGN2F=1.
C
C     LATEST AND EARLIEST POSSIBLE VALUES OF PHI2 AND PHIS FOR MESH 2
C
   68 DO 69 I=1,2000
```

```
      PHID2=PHI2TO-(I-1.)/100.
      PHI2=PHID2*ZZ
      A2F=AG2*COS(PHI2+DELG2+ALPHP2)-B2*COS(BETA2+ALPHP2)
      B2F=-AG2*SIN(PHI2+DELG2+ALPHP2)+B2*SIN(BETA2+ALPHP2)
      C2F=RHOG2
      ROOT2F=A2F**2+B2F**2-C2F**2
      Y2F=A2F+SIGN2F*SQRT(ROOT2F)
      X2F=B2F+C2F
      PHISF=2.*ATAN2(Y2F,X2F)
      LX2=B2*COS(BETA2)+AP2*COS(PHISF-DPHIS+DELP2)-AG2*COS(PHI2+DPHI2+
     1DELG2)
      LY2=B2*SIN(BETA2)+AP2*SIN(PHISF-DPHIS+DELP2)-AG2*SIN(PHI2+DPHI2+
     1DELG2)
      LL2=SQRT(LX2**2+LY2**2)
      DELEL2=LL2-L2
      IF(DELEL2.LE.0)GO TO 70
   69 CONTINUE
   70 PHI2F=PHI2
      PHISFF=PHISF
      IF(PHIST-PHISFF.GT..001)PHISFF=PHISFF+2.*PI
      PHI2I=PHI2F+DPHI2
      PHISI=PHISFF-DPHIS
      PHI2ID=PHI2I/ZZ
      PHISID=PHISI/ZZ
      PHI2FD=PHI2F/ZZ
      PHISFD=PHISFF/ZZ
      WRITE(6,74)PHI2ID,PHISID,PHI2FD,PHISFD
   74 FORMAT(6X,*PHI2ID =*,F7.3,5X,*PHISID =*,F7.3,5X,
     +*PHI2FD =*,F7.3,5X,*PHISFD =*,F7.3)
C
C     DETERMINATION OF CORRECT SIGN FOR FORWARD ROUND-ON-ROUND REGIME
C     OF MESH 2
C
      A2R=AG2*SIN(PHI2I+DELG2-DELP2)-B2*SIN(BETA2-DELP2)
      B2R=AG2*COS(PHI2I+DELG2-DELP2)-B2*COS(BETA2-DELP2)
      C2R=(AP2**2+AG2**2+B2**2-L2**2-2.*AG2*B2*COS(PHI2I+DELG2-BETA2))/
     1(2.*AP2)
      ROOT2R=A2R**2+B2R**2-C2R**2
      Y2R1=A2R+SQRT(ROOT2R)
      Y2R2=A2R-SQRT(ROOT2R)
      X2R=B2R+C2R
      PHISR1=2.*ATAN2(Y2R1,X2R)
      PHISR2=2.*ATAN2(Y2R2,X2R)
      IF(PHISR1.LT.0)PHISR1=PHISR1+2.*PI
      IF(PHISR2.LT.0)PHISR2=PHISR2+2.*PI
      IF(ABS(PHISI-PHISR1).LT.ABS(PHISI-PHISR2))GO TO 71
      SIGN2R=-1.
      GO TO 82
   71 SIGN2R=1.
C
C     REVERSE KINEMATICS OF MESH 2
C
C     DETERMINATION OF CORRECT SIGN FOR REVERSE ROUND-ON-ROUND REGIME
C     FOR MESH 2
C
   82 D2R=-2.*AP2*AG2*SIN(PHISI+DELP2-DELG2)-2[illegible]G2*B2*SIN(BETA2-DELG2)
      E2R=-2.*AP2*AG2*COS(PHISI+DELP2-DELG2)-[illegible]2*B2*COS(BETA2-D[illegible]G2)
```

```
      F2R=L2**2-AG2**2-AP2**2-B2**2-2.*AP2*B2*COS(PHISI+DELP2-BETA2)   004700
      ROOT2R=D2R**2+E2R**2-F2R**2                                      004710
      Y2R1=D2R+SQRT(ROOT2R)                                            004720
      Y2R2=D2R-SQRT(ROOT2R)                                            004730
      X2R=E2R+F2R                                                      004740
      PHI2R1=2.*ATAN2(Y2R1,X2R)                                        004750
      PHI2R2=2.*ATAN2(Y2R2,X2R)                                        004760
      IF(PHI2R1.LT.O)PHI2R1=PHI2R1+2.*PI                               004770
      IF(PHI2R2.LT.O)PHI2R2=PHI2R2+2.*PI                               004780
      WRITE(6,666)PHI2I,PHI2R1,PHI2R2                                  004790
  666 FORMAT(* PHI2I =*,E12.4,3X,*PHI2R1 =*,E12.4,3X,*PHI2R2 =*,E12.4) 004800
      IF(ABS(PHI2I-PHI2R1).LT.(PHI2I-PHI2R2))GO TO 83                  004810
      RSGN2R=-1.                                                       004820
      GO TO 84                                                         004830
   83 RSGN2R=1.                                                        004840
C                                                                      004850
C     DETERMINATION OF CORRECT SIGN FOR REVERSE ROUND-ON-FLAT REGIME   004860
C     FOR MESH 2                                                       004870
C                                                                      004880
   84 D2F=-AG2*COS(PHISFF-ALPHP2-DELG2)                                004890
      E2F=AG2*SIN(PHISFF-ALPHP2-DELG2)                                 004900
      F2F=RHOG2+B2*SIN(PHISFF-ALPHP2-BETA2)                            004910
      ROOT2F=D2F**2+E2F**2-F2F**2                                      004920
      Y2F1=D2F+SQRT(ROOT2F)                                            004930
      Y2F2=D2F-SQRT(ROOT2F)                                            004940
      X2F=E2F+F2F                                                      004950
      PHI2F1=2.*ATAN2(Y2F1,X2F)                                        004960
      PHI2F2=2.*ATAN2(Y2F2,X2F)                                        004970
      IF(PHI2F1.LT.O)PHI2F1=PHI2F1+2.*PI                               004980
      IF(PHI2F2.LT.O)PHI2F2=PHI2F2+2.*PI                               004990
      IF(ABS(PHI2F1-PHI2F).LT.ABS(PHI2F2-PHI2F))GO TO 85               005000
      RSGN2F=-1.                                                       005010
      GO TO 86                                                         005020
   85 RSGN2F=1.                                                        005030
C                                                                      005040
C     DATA FOR RUNGE KUTTA                                             005050
C                                                                      005060
   86 DIFF1=PH2PFF-PH2PI                                               005070
      PHI2P=J1*DIFF1+PH2PI                                             005080
      DIFF2=PHISFF-PHISI                                               005090
      PHIS=J2*DIFF2+PHISI                                              005100
      ALPHR=ALPHEN                                                     005110
      PRMT(2)=3.                                                       005120
      PRMT(4)=.01                                                      005130
      NDIM=2                                                           005140
      NDIM2=4                                                          005150
      PHI(1)=PHID*ZZ                                                   005160
      PHI(2)=O                                                         005170
C                                                                      005180
C     COUPLED MOTION                                                   005190
C                                                                      005200
    1 PRMT(1)=TIME                                                     005210
      PRMT(3)=.00001                                                   005220
      DPHI(1)=.5                                                       005230
      DPHI(2)=.5                                                       005240
      IF(PHITOT.GT.30..AND.PHITOT.LT.1450.)GO TO 2                     005250
      WRITE(6,45)                                                      005260
```

```
    2 CALL RKGS(PRMT,PHI,DPHI,NDIM,IHLF,FCT,OUTP,AUX)             005270
      IF(PHITOT.GT.PHICUTD)GO TO 16                               005280
C                                                                 005290
C     TEST FOR ENTRANCE OR EXIT ACTION                            005300
C                                                                 005310
      IF(PN.LE.O)GO TO 5                                          005320
      PHID=PHI(1)/ZZ                                              005330
      IF(PHID.GE.130..AND.PHID.LE.160.)GO TO 3                    005340
      GO TO 4                                                     005350
    3 PHI(1)=PHI(1)+DELTA*ZZ*NT                                   005360
      PHIPR=PHI(1)/ZZ                                             005370
      PSI=PSI+2.*PI-LAMBDA*ZZ                                     005380
      PSIC=PSICC+LAMBDA*ZZ                                        005390
      ALPHR=ALPHEX                                                005400
      GO TO 5                                                     005410
    4 PHI(1)=PHI(1)-DELTA*ZZ*(NT+1.)                              005420
      PHIPR=PHI(1)/ZZ                                             005430
      PSI=PSI-2.*PI+LAMBDA*ZZ                                     005440
      ALPHR=ALPHEN                                                005450
      PSIC=PSICC                                                  005460
C                                                                 005470
C     FREE MOTION                                                 005480
C                                                                 005490
    5 PRMT(1)=TIME                                                005500
      X(1)=PHI(1)                                                 005510
      X(2)=PHI(2)                                                 005520
      X(3)=PSI                                                    005530
      X(4)=DPSI                                                   005540
      DX(1)=.25                                                   005550
      DX(2)=.25                                                   005560
      DX(3)=.25                                                   005570
      DX(4)=.25                                                   005580
      PRMT(3)=.00001                                              005590
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 6              005600
      WRITE (6,46)                                                005610
    6 CALL RKGS (PRMT,X,DX,NDIM2,IHLF,FCTF,OUTPF,AUX2)            005620
      IF (PHITOT.GT.PHICUTD) GO TO 16                             005630
      PHI(1)=X(1)                                                 005640
      PHI(2)=X(2)                                                 005650
      PSI=X(3)                                                    005660
      DPSI=X(4)                                                   005670
      G=(B*SIN(PHI(1))-C*SIN(PSI))/SIN(PSI+ALPHR)                 005680
      PHID=PHI(1)/ZZ                                              005690
      IF (PHID.LT.160..AND.GP.GT.O.) GO TO 10                     005700
      IF (PHID.GT.160..AND.GP.LT.O.) GO TO 8                      005710
      IF (PHID.LT.160.) GO TO 7                                   005720
      PHI(1)=PHI(1)-DELTA*ZZ*(NT+1.)                              005730
      PHIPR=PHI(1)/ZZ                                             005740
      PSI=PSI-2.*PI+LAMBDA*ZZ                                     005750
      PSIC=PSICC                                                  005760
      GO TO 5                                                     005770
    7 PHI(1)=PHI(1)+DELTA*ZZ*NT                                   005780
      PHIPR=PHI(1)/ZZ                                             005790
      PSI=PSI+2.*PI-LAMBDA*ZZ                                     005800
      PSIC=PSICC+LAMBDA*ZZ                                        005810
      GO TO 5                                                     005820
C                                                                 005830
```

```
C     EXIT ACTION
C
C     COMPUTATION OF VELOCITIES VP AND VS FOR EXIT ACTION
C
    8 VP=DPSI*(C*COS(ALPHR)+G)
      VS=PHI(2)*B*COS(PHI(1)-PSI-ALPHR)
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 9
      WRITE (6,47) VP,VS
C
C     EXIT ACTION TESTS
C
    9 IF (PHI(2).GE.O..AND.DPSI.GE.O.) GO TO 12
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 5
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 12
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      IF (PHI(2).LE.O..AND.DPSI.GE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 12
      IF (PHI(2).LE.O..AND.DPSI.GE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 5
      IF (PHI(2).LE.O..AND.DPSI.GE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      IF (PHI(2).LE.O..AND.DPSI.LE.O.) GO TO 5
C
C     COMPUTATION OF VELOCITIES VP AND VS FOR ENTRANCE ACTION
C
   10 VP=DPSI*(C*COS(ALPHR)+G)
      VS=PHI(2)*B*COS(PHI(1)-PSI-ALPHR)
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 11
      WRITE (6,47) VP,VS
C
C     ENTRANCE ACTION
C
   11 IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 5
      IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 12
      IF (PHI(2).LE.O..AND.DPSI.GE.O.) GO TO 5
      IF (PHI(2).GE.O..AND.DPSI.LE.O.) GO TO 12
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 5
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 12
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
C
C     IMPACT
C
   12 CALL IMPACT (PHI(1),PHI(2),PSI,DPSI)
      IF (TIME.GT.5.0) GO TO 16
C
C     TEST FOR EXIT ACTION
C
      PHID=PHI(1)/ZZ
      IF (PHID.LE.160.0) GO TO 14
C
C     EXIT ACTION
C
C     COMPUTATION OF VELOCITIES VP AND VS FOR EXIT ACTION
      VP=DPSI*(C*COS(ALPHR)+G)
      VS=PHI(2)*B*COS(PHI(1)-PSI-ALPHR)
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 13
      WRITE (6,47) VP,VS
   13 IF (ABS(ABS(VP)-ABS(VS)).LT.2.0) GO TO 1
C
```

```
C     EXIT ACTION TESTS                                                  006410
C                                                                        006420
      IF (PHI(2).GE.O..AND.DPSI.GE.O.) GO TO 1                           006430
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 5    006440
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 1    006450
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1    006460
      IF (PHI(2).LE.O..AND.DPSI.GT.O..AND.ABS(VP).LT.ABS(VS)) GO TO 5    006470
      IF (PHI(2).LE.O..AND.DPSI.GT.O..AND.ABS(VP).GT.ABS(VS)) GO TO 1    006480
      IF (PHI(2).LE.O..AND.DPSI.GT.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1    006490
      IF (PHI(2).LE.O..AND.DPSI.LE.O.) GO TO 5                           006500
C                                                                        006510
C     COMPUTATION OF VELOCITIES VP AND VS FOR ENTRANCE ACTION            006520
C                                                                        006530
   14 VP=DPSI*(C*COS(ALPHR)+G)                                           006540
      VS=PHI(2)*B*COS(PHI(1)-PSI-ALPHR)                                  006550
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 15                    006560
      WRITE (6,47) VP,VS                                                 006570
   15 IF (ABS(ABS(VP)-ABS(VS)).LT.2.0) GO TO 1                           006580
C                                                                        006590
C     ENTRANCE ACTION TESTS                                              006600
C                                                                        006610
      IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 5    006620
      IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 1    006630
      IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1    006640
      IF (PHI(2).LE.O..AND.DPSI.GE.O.) GO TO 5                           006650
      IF (PHI(2).GE.O..AND.DPSI.LE.O.) GO TO 1                           006660
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 1    006670
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 5    006680
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1    006690
   16 TURNS=RPM*TIME/60.                                                 006700
      WRITE(6,48)F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,                006710
     +F12FRMX,F23FFMX,F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,           006720
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PNMAX,TURNS                        006730
      STOP                                                               006740
C                                                                        006750
C                                                                        006760
C                                                                        006770
   17 FORMAT (6E12.4)                                                    006780
   18 FORMAT (1H ,5X,6HIXX1 =,E13.4,3X,6HIEE1 =,E13.4,3X,6HIZZ1 =,E13.4,006790
     13X,6HIXE1 =,E13.4,3X,6HIZX1 =,E13.4,3X,6HIEZ1 =,E13.4/)            006800
   19 FORMAT (3E12.4)                                                    006810
   20 FORMAT (1H ,5X,5HIX2 =,E13.4,3X,5HIY2 =,E13.4,3X,5HIZ2 =,E13.4/)   006820
   21 FORMAT (1H ,5X,5HIXS =,E13.4,3X,5HIYS =,E13.4,3X,5HIZS =,E13.4/)   006830
   22 FORMAT (1H ,5X,6HIXXP =,E13.4,3X,6HIEEP =,E13.4,3X,6HIZZP =,E13.4,006840
     13X,6HIXEP =,E13.4,3X,6HIZXP =,E13.4,3X,6HIEZP =,E13.4/)            006850
   23 FORMAT (2F10.5)                                                    006860
   24 FORMAT (6X,4HLU =,F5.3,3X,4HLL =,F5.3/)                            006870
   25 FORMAT (6X,7HRHOF1 =,F6.4,3X,7HRHOF2 =,F6.4,3X,7HRHOF3 =,F6.4,3X,6006880
     1HRHOF =,F6.4/)                                                     006890
   26 FORMAT(6X,4HRX =,F8.3,3X,4HRY =,F8.3,3X,4HRZ =,F8.3,3X,            006900
     +4HS8 =,F4.0/)                                                      006901
   27 FORMAT (7F10.5)                                                    006910
   28 FORMAT (1H1,5X,2HA=,F13.5,5X,2HB=,F13.5,5X,2HC=,F13.5,5X,7HALPHEN=006920
     1,F9.4,5X,7HALPHEX=,F9.4//6X,3HNT=,F3.0,5X,8HCONFIG =,F3.0/)        006930
   29 FORMAT (4F10.5)                                                    006940
   30 FORMAT (1H ,5X,6HEREST=,F5.2,3X,7HLAMBD[illegible]8.3,3X,3HN =,F4.0/)    006950
   31 FORMAT (4E12.5)                                                    006960
```

```
      32 FORMAT (1H ,5X,4HM1 =,E15.5,3X,4HM2 =,E15.5,3X,4HM3 =,E15.5,3X,4HM006970
     1P =,E15.5/)                                                       006980
      33 FORMAT (7F10.4/3F10.4)                                         006990
      34 FORMAT (6X,5HRC1 =,F7.4,3X,5HRCP =,F7.4,3X,6HRHOP =,F7.4,3X,5HRPM 007000
     +*,F6.0,3X,9HPHI1RCD =,F9.4,3X,8HPSICCD =,F9.4,3X,6HPHID =,F9.4//6X007010
     2,9HPHICUTD =,F6.0//6X,4HMU =,F4.2,3X,5HMU1 =,F4.2/)               007020
      35 FORMAT(4F10.4/4F10.4)                                          007030
      36 FORMAT(4F10.4)                                                 007040
      37 FORMAT (2F10.2)                                                007050
      38 FORMAT(1H ,5X,*NG1 =*,F4.0                                     007060
     1,3X,5HNG2 =,F4.0,3X,5HNP2 =,F4.0,3X,5HNP3 =,F4.0//6X,8HCAPRP1 =,F8007070
     +.5,3X,*CAPRP2 =*,F8.5//6X,*RP2 =*,F8.5,3X,*RP3 =*,F8.5/)          007080
      39 FORMAT (6X,4HR1 =,F7.5,3X,4HR2 =,F7.5,3X,4HR3 =,F7.5,3X,4HR4 =,F7.007090
     15/)                                                               007100
      40 FORMAT (6X,6HRHO1 =,F7.5,3X,6HRHO2 =,F7.5,3X,6HRHO3 =,F7.5/)   007110
      43 FORMAT (1H ,5X,4HJ1 =,F4.2,3X,4HJ2 =,F4.2/)                    007120
      44 FORMAT (6X,8HBETA1D =,F7.2,3X,8HBETA2D =,F7.2,3X,8HBETA3D =,F7.2/6007130
     1X,9HGAMMA2D =,F7.2,3X,9HGAMMA3D =,F7.2,3X,9HGAMMA4D =,F7.2)       007140
      45 FORMAT (1HO,5X,14HCOUPLED MOTION)                              007150
      46 FORMAT (1HO,5X,11HFREE MOTION//)                               007160
      47 FORMAT (4HOVP=,F8.3,3X,3HVS=,F8.3)                             007170
      48 FORMAT(1HO,6X,*F23RRMX =*,F6.2,3X,*F12RRMX =*,F6.2/1HO,6X,     007180
     +*F23RFMX =*,F6.2,3X,*F12RFMX =*,F6.2/1HO,6X,*F23FRMX =*,F6.2,     007190
     +3X,*F12FRMX =*,F6.2/1HO,6X,*F23FFMX =*,F6.2,3X,*F12FFMX =*,       007200
     +F6.2/1HO,6X,*T23RRMX =*,F6.2,3X,*T12RRMX =*,F6.2/1HO,6X,          007210
     +*T23RFMX =*,F6.2,3X,*T12RFMX =*,F6.2/1HO,6X,*T23FRMX =*,          007220
     +F6.2,3X,*T12FRMX =*,F6.2/1HO,6X,*T23FFMX =*,F6.2,3X,              007230
     +*T12FFMX =*,F6.2/1HO,6X,*PNMAX =*,F6.2//1HO,6X,                   007240
     +*NUMBER OF TURNS TO ARM =*,F8.3)                                  007250
         END                                                            007260
```

```
      SUBROUTINE ACCEL (RX,RY,RZ,GAMMA2,GAMMA3,GAMAPP,R1,R2,R3,R4,BETA3,007270
     1GX,GY,GZ,HX,HY,HZ,KX,KY,KZ,JX,JY,JZ,NX,NY,NZ,LX,LY,LZ,OX,OY,OZ,PX,007280
     +PY,PZ,QX,QY,QZ,T,DDZ)                                             007290
      COMMON /DATA/ RPM                                                 007300
      COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,SB                        007310
      REAL KX,KY,KZ,JX,JY,JZ,NX,NY,NZ,LX,LY,LZ                          007320
      CALL AERO(RPM,T,DDZ)                                              007330
      GX=(OMY*RY+OMZ*RZ)*OMX-(OMY**2+OMZ**2)*RX+(DOMY*RZ-DOMZ*RY)       007340
      GY=(OMX*RX+OMZ*RZ)*OMY-(OMX**2+OMZ**2)*RY+(DOMZ*RX-DOMX*RZ)       007350
      GZ=(OMX*RX+OMY*RY)*OMZ-(OMX**2+OMY**2)*RZ+(DOMX*RY-DOMY*RX)+DDZ   007360
      R4X=-R4*COS(GAMAPP+BETA3)                                         007370
      R4Y=-R4*SIN(GAMAPP+BETA3)                                         007380
      HX=OMY*OMX*R4Y-(OMY**2+OMZ**2)*R4X-DOMZ*R4Y                       007390
      HY=OMX*OMY*R4X-(OMX**2+OMZ**2)*R4Y+DOMZ*R4X                       007400
      HZ=(OMX*R4X+OMY*R4Y)*OMZ+(DOMX*R4Y-DOMY*R4X)                      007410
      KX=-(GX+HX)*COS(BETA3)-(GY+HY)*SIN(BETA3)                         007420
      KY=(GX+HX)*SIN(BETA3)-(GY+HY)*COS(BETA3)                          007430
      KZ=GZ+HZ                                                          007440
      R3X=R3*COS(GAMMA3)                                                007450
      R3Y=R3*SIN(GAMMA3)                                                007460
      JX=OMX*OMY*R3Y-(OMY**2+OMZ**2)*R3X-DOMZ*R3Y                       007470
      JY=OMX*OMY*R3X-(OMX**2+OMZ**2)*R3Y+DOMZ*R3X                       007480
      JZ=(OMX*R3X+OMY*R3Y)*OMZ+DOMX*R3Y-DOMY*R3X                        007490
      NX=GX+JX                                                          007500
      NY=GY+JY                                                          007510
      NZ=GZ+JZ                                                          007520
      LX=-(OMY**2+OMZ**2)*R1                                            007530
      LY=(OMX*OMY+DOMZ)*R1                                              007540
      LZ=(OMX*OMZ-DOMY)*R1                                              007550
      OX=GX+LX                                                          007560
      OY=GY+LY                                                          007570
      OZ=GZ+LZ                                                          007580
      R2X=R2*COS(GAMMA2)                                                007590
      R2Y=R2*SIN(GAMMA2)                                                007600
      PX=OMX*OMY*R2Y-(OMY**2+OMZ**2)*R2X-DOMZ*R2Y                       007610
      PY=OMX*OMY*R2X-(OMX**2+OMZ**2)*R2Y+DOMZ*R2X                       007620
      PZ=(OMX*R2X+OMY*R2Y)*OMZ+DOMX*R2Y-DOMY*R2X                        007630
      QX=GX+PX                                                          007640
      QY=GY+PY                                                          007650
      QZ=GZ+PZ                                                          007660
      RETURN                                                            007670
      END                                                               007680
```

```
      SUBROUTINE AWON (S6,S7,ALPHR,BETA3,RCP,MP,IXXP,IEEP,IZZP,IXEP,IZXP007690
     +,IEZP,MU1,S4,S5,PSI,PSIC,KX,KY,KZ,AA1,A                          007700
     2A2,AA3,AA4,AA5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,007710
     3AA17,AA18,AA19,AA20,AA21,AA22,AA23,PHITOT)                       007720
      REAL IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,KX,KY,KZ,MP,MU1               007730
      COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8                        007740
      BETA=PSI+PSIC                                                     007750
      ALPHAP=BETA+BETA3                                                 007760
      SA=SIN(ALPHAP)                                                    007770
      CA=COS(ALPHAP)                                                    007780
      SB=SIN(BETA)                                                      007790
      CB=COS(BETA)                                                      007800
      AA1=CB*(-IXXP*(DOMX*CA+DOMY*SA)+(IZZP-IEEP)*OMZ*(OMX*SA-OMY*CA)-IX007810
     1EP*(OMZ*(OMX*CA+OMY*SA)+(DOMX*SA-DOMY*CA))+IZXP*((OMX*CA+OMY*SA)*(007820
     2OMX*SA-OMY*CA)-DOMZ)-IEZP*((OMX*SA-OMY*CA)**2-OMZ**2))-SB*(IEEP*(D007830
     3OMX*SA-DOMY*CA)-(IXXP-IZZP)*OMZ*(OMX*CA+OMY*SA)-IEZP*((OMX*CA+OMY*007840
     4SA)*(OMX*SA-OMY*CA)+DOMZ)+IXEP*((DOMX*CA+DOMY*SA)-OMZ*(OMX*SA-OMY*007850
     5CA))-IZXP*(OMZ**2-(OMX*CA+OMY*SA)**2))                           007860
      AA2=(OMX*SA-OMY*CA)*((IXXP+IZZP-IEEP)*CB+2.*IXEP*SB)-(OMX*CA+OMY*S007870
     1A)*(2.*IXEP*CB+(IEEP-IXXP+IZZP)*SB)+2.*OMZ*(IEZP*CB+IZXP*SB)     007880
      AA3=IEZP*CB+IZXP*SB                                               007890
      AA4=IEZP*SB-IZXP*CB                                               007900
      AA5=SB*(-IXXP*(DOMX*CA+DOMY*SA)+(IZZP-IEEP)*OMZ*(OMX*SA-OMY*CA)+IX007910
     1EP*(-OMZ*(OMX*CA+OMY*SA)-(DOMX*SA-DOMY*CA))-IZXP*(-(OMX*CA+OMY*SA)007920
     2*(OMX*SA-OMY*CA)+DOMZ)-IEZP*((OMX*SA-OMY*CA)**2-OMZ**2))+CB*(IEEP*007930
     3(DOMX*SA-DOMY*CA)-(IXXP-IZZP)*OMZ*(OMX*CA+OMY*SA)+IEZP*(-(OMX*CA+O007940
     4MY*SA)*(OMX*SA-OMY*CA)-DOMZ)-IXEP*(-(DOMX*CA+DOMY*SA)+OMZ*(OMX*SA-007950
     5OMY*CA))-IZXP*(OMZ**2-(OMX*CA+OMY*SA)**2))                       007960
      AA6=(OMX*SA-OMY*CA)*((IXXP+IZZP-IEEP)*SB-2.*IXEP*CB)+(OMX*CA+OMY*S007970
     1A)*((IEEP-IXXP+IZZP)*CB-2.*IXEP*SB)+2.*OMZ*(IEZP-IZXP)           007980
      AA7=IEZP*SB-IZXP*CB                                               007990
      AA8=-(IZXP*SB+IEZP*CB)                                            008000
      AA9=IZZP*DOMZ-(IEEP-IXXP)*((OMX*CA+OMY*SA)*(OMX*SA-OMY*CA))+IZXP*(008010
     1OMZ*(OMX*SA-OMY*CA)+(DOMX*CA+DOMY*SA))-IEZP*((DOMX*SA-DOMY*CA)-OMZ008020
     2*(OMX*CA+OMY*SA))-IXEP*((OMX*CA+OMY*SA)**2-(OMX*SA-OMY*CA)**2)   008030
      AA10=IZZP                                                         008040
      AA11=MU1*S5                                                       008050
      AA12=MP*RCP*(-OMX*OMX*SIN(BETA3)*SA-OMY*OMY*COS(BETA3)*CA+OMX*OMY*008060
     1SIN(ALPHAP+BETA3)-OMZ**2*CB-DOMZ*SB)+MP*KX                       008070
      AA13=-2.*OMZ*MP*RCP*CB                                            008080
      AA14=-MP*RCP*CB                                                   008090
      AA15=-MP*RCP*SB                                                   008100
      AA16=-(MU1*S4*COS(PSI+ALPHR)-S7*SIN(PSI+ALPHR))                   008110
      AA17=MP*RCP*(-OMX**2*COS(BETA3)*SA+OMY**2*SIN(BETA3)*CA-OMX*OMY*CO008120
     1S(ALPHAP+BETA3)-OMZ**2*SB+DOMZ*CB)+MP*KY                         008130
      AA18=-2.*MP*RCP*OMZ*SB                                            008140
      AA19=-MP*RCP*SB                                                   008150
      AA20=MP*RCP*CB                                                    008160
      AA21=-(COS(PSI+ALPHR)*S7+MU1*S4*SIN(PSI+ALPHR))                   008170
      AA22=ABS(MP*RCP*(-(DOMX+OMY*OMZ)*SA+(DOMY-OMX*OMZ)*CA)+MP*KZ)     008180
      AA23=ABS(-2.*MP*RCP*(OMX*CA+OMY*SA))                              008190
      RETURN                                                            008200
      END                                                               008210
```

```
      SUBROUTINE CWON (LU,LL,MU1,S5,MP,RCP,PSI,PSIC,KX,KY,KZ,AA1,AA2,AA3008220
     1,AA4,AA5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,A008230
     2A18,AA19,AA20,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,C008240
     3C10,CC11,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20)           008250
      REAL LU,LL,MP,MU1,KX,KY,KZ                                        008260
      BETA=PSI+PSIC                                                     008270
      SB=SIN(BETA)                                                      008280
      CB=COS(BETA)                                                      008290
      CC1=ABS(-LL*AA12+MU1*S5*(AA1-LL*AA17)-AA5+MP*RCP*KZ*(MU1*S5*SB+CB)008300
     1)                                                                 008310
      CC2=ABS(-LL*AA13+MU1*S5*(AA2-LL*AA18)-AA6)                        008320
      CC3=ABS(-LL*AA14+MU1*S5*(AA3-LL*AA19)-AA7)                        008330
      CC4=ABS(-LL*AA15+MU1*S5*(AA4-LL*AA20)-AA8)                        008340
      CC5=ABS(-LL*AA16-MU1*S5*LL*AA21)                                  008350
      CC6=ABS(AA1-LL*AA17+MU1*S5*(LL*AA12+AA5)+MP*RCP*KZ*(SB-MU1*S5*CB))008360
      CC7=ABS(AA2-LL*AA18+MU1*S5*(AA6+LL*AA13))                         008370
      CC8=ABS(AA3-LL*AA19+MU1*S5*(AA7+LL*AA14))                         008380
      CC9=ABS(AA4-LL*AA20+MU1*S5*(LL*AA15-AA8))                         008390
      CC10=ABS(MU1*S5*LL*AA16-LL*AA21)                                  008400
      CC11=ABS(LU*AA12-AA5+MU1*S5*(LU*AA17+AA1)+MP*RCP*KZ*(MU1*S5*SB+CB)008410
     1)                                                                 008420
      CC12=ABS(LU*AA13-AA6+MU1*S5*(LU*AA18+AA2))                        008430
      CC13=ABS(LU*AA14-AA7+MU1*S5*(LU*AA19+AA3))                        008440
      CC14=ABS(LU*AA15-AA8+MU1*S5*(LU*AA20+AA4))                        008450
      CC15=ABS(LU*AA16+MU1*S5*LU*AA21)                                  008460
      CC16=ABS(LU*AA17+AA1+MU1*S5*(AA5-LU*AA12)+MP*RCP*KZ*(SB-MU1*S5*CB)008470
     1)                                                                 008480
      CC17=ABS(LU*AA18+AA2+MU1*S5*(AA6-LU*AA13))                        008490
      CC18=ABS(LU*AA19+AA3+MU1*S5*(AA7-LU*AA14))                        008500
      CC19=ABS(LU*AA20+AA4+MU1*S5*(AA8-LU*AA15))                        008510
      CC20=ABS(LU*AA21-MU1*S5*LU*AA16)                                  008520
      RETURN                                                            008530
      END                                                               008540
```

```
      SUBROUTINE ATWO(S7,CONE,DONE,DPSI,PSI,                            008550
     1NX,NY,NZ,AA16,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,C008560
     2C10,CC11,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20,AA24,AA25,AA008570
     +26,AA27,AA28,AA29,AA30,AA31,AA32,AA33,AA34R,AA34F,AA35,AA36,      008580
     +AA37R,AA37F,AA38,AA39,AA40,AA41,AA42,IPR)                         008590
      COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,    008600
     +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY, 008610
     +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,  008620
     +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,      008630
     +GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,     008640
     +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,    008650
     +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,           008660
     +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2         008670
     +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2                              008680
     +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,         008690
     +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,                          008700
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F 008710
      COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,SR                        008720
      COMMUN/DATA5/LU,LL,MU,MU1                                         008730
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,            008740
     +PHI2P,PHI1,PHI2,GAM                                               008750
      REAL LU,LL,LT,MU,MU1,IPR,IZZP,NX,NY,NZ,M3,IXS,IYS,IZS,LAMDA2      008760
      X=(LL+LU)*(1.+MU1**2)                                             008770
      AA24=(CC1+CC6+CC11+CC16)/X                                        008780
      AA25=(CC2+CC7+CC12+CC17)/X                                        008790
      AA26=(CC3+CC8+CC13+CC18)/X                                        008800
      AA27=(CC4+CC9+CC14+CC19)/X                                        008810
      AA28=(CC5+CC10+CC15+CC20)/X                                       008820
      AA29=S7*DONE-CONE*MU1*S4-MU1*RHOP*S5*AA28                         008830
      AA30=MU1*S5*(RHOF*AA22+RHOP*AA24)                                 008840
      AA31=MU1*(RHOF*AA23+RHOP*AA25)                                    008850
      AA32=MU1*S5*RHOP*AA26                                             008860
      AA333=MU1*RHOP*AA27                                               008870
      IF (DPSI*DPSI2.GE.0) IPR=IZZP+AA333                               008880
      IF (DPSI*DPSI2.LT.0) IPR=IZZP-AA333                               008890
      IF (IPR.LT.0) IPR=0                                               008900
      AA33=MU1*S4*COS(PSI+ALPHR+BETA3)-S7*SIN(PSI+ALPHR+BETA3)          008910
      AA34R=COS(LAMDA2)-MU*S2R*SIN(LAMDA2)                              008920
      AA34F=-SIN(PHIS-ALPHP2)+MU*S2F*COS(PHIS-ALPHP2)                   008930
      AA35=-NX*M3                                                       008940
      AA36=S7*COS(PSI+ALPHR+BETA3)+MU1*S4*SIN(PSI+ALPHR+BETA3)          008950
      AA37R=SIN(LAMDA2)+MU*S2R*COS(LAMDA2)                              008960
      AA37F=COS(PHIS-ALPHP2)+MU*S2F*SIN(PHIS-ALPHP2)                    008970
      AA38=-NY*M3                                                       008980
      AA39=IXS*DOMX+OMY*OMZ*(IZS-IYS)                                   008990
      AA40=IZS*OMY                                                      009000
      AA41=IYS*DOMY+OMX*OMZ*(IXS-IZS)                                   009010
      AA42=-IZS*OMX                                                     009020
      RETURN                                                            009030
      END                                                               009040
```

```
      SUBROUTINE CTWO(LU,LL,MU,S6,AA33,AA34R,AA34F,AA35,AA36,AA37R,     009050
     +AA37F,AA38,AA39,AA40,AA41,AA42,CC21,CC22,CC23R,CC23F,             009060
     +CC24,CC25,CC26,CC27R,CC27F,CC28,CC29,CC30,CC31R,CC31F,            009070
     +CC32,CC33,CC34,CC35R,CC35F,CC36)                                  009080
      REAL LL,LU,MU                                                     009090
      CC21=ABS(LL*AA35-AA41+MU*(LL*AA38+AA39))                          009100
      CC22=ABS(LL*(AA33+MU*AA36))                                       009110
      CC23R=ABS(LL*(AA34R+MU*AA37R))                                    009120
      CC23F=ABS(LL*(AA34F+MU*AA37F))                                    009130
      CC24=ABS(MU*AA40-AA42)                                            009140
      CC25=ABS(LL*AA38+AA39+MU*(AA41-LL*AA35))                          009150
      CC26=ABS(LL*(AA36-MU*AA33))                                       009160
      CC27R=ABS(LL*(AA37R-MU*AA34R))                                    009170
      CC27F=ABS(LL*(AA37F-MU*AA34F))                                    009180
      CC28=ABS(AA40+MU*AA42)                                            009190
      CC29=ABS(MU*(AA39-LU*AA38)-LU*AA35-AA41)                          009200
      CC30=ABS(LU*(AA33+MU*AA36))                                       009210
      CC31R=ABS(LU*(AA34R+MU*AA37R))                                    009220
      CC31F=ABS(LU*(AA34F+MU*AA37F))                                    009230
      CC32=ABS(MU*AA40-AA42)                                            009240
      CC33=ABS(MU*(AA41+LU*AA35)+AA39-LU*AA38)                          009250
      CC34=ABS(LU*(MU*AA33-AA36))                                       009260
      CC35R=ABS(LU*(MU*AA34R-AA37R))                                    009270
      CC35F=ABS(LU*(MU*AA34F-AA37F))                                    009280
      CC36=ABS(AA40+MU*AA42)                                            009290
      RETURN                                                            009300
      END                                                               009310
```

```
      SUBROUTINE ATHREE(S7,DPHI,AONE,BONE,NZ                                 009320
     +,CC21,CC22,CC23R,CC23F,CC24,CC25,CC26,CC27R,CC27F,CC28,                009330
     +CC29,CC30,CC31R,CC31F,CC32,CC33,CC34,CC35R,CC35F,CC36,AA43,AA44,       009340
     +AA45R,AA45F,AA46,AA47,AA48,AA49R,AA49F,AA50,AA51,AA52,AA53,AA54,       009350
     +AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65                 009360
     +,AA66R,AA66F,AA67,AA68,AA69,AA70,AA71R,AA71F)                          009370
      COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,         009380
     +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,      009390
     +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,       009400
     +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,           009410
     +GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,          009420
     +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,         009430
     +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,                009440
     +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2              009450
     +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2                                   009460
     +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,              009470
     +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,                               009480
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F      009490
      COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8                             009500
      COMMON/DATA2/KX,KY,OX,OY,OZ,QX,QY,QZ                                   009510
      COMMON/DATA5/LU,LL,MU,MU1                                              009520
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,                 009530
     +PHI2P,PHI1,PHI2,GAM                                                    009540
      REAL LU,LL,MU,M3,NX,NY,NZ,IZS,MU1, IXX1,IZZ1,IEE1,IXE1,IZX1,IEZ        009550
     11,M1,M2,LAMDA1,LAMDA2                                                  009560
      XX=(LU+LL)*(1.+MU**2)                                                  009570
      AA43=(CC21+CC25+CC29+CC33)/XX                                          009580
      AA44=(CC22+CC26+CC30+CC34)/XX                                          009590
      AA45R=(CC23R+CC27R+CC31R+CC35R)/XX                                     009600
      AA45F=(CC23F+CC27F+CC31F+CC35F)/XX                                     009610
      AA46=(CC24+CC28+CC32+CC36)/XX                                          009620
      AA47=ABS(NZ*M3)                                                        009630
      IF (DPHI.EQ.0) GO TO 1                                                 009640
      AA48=MU*RHO3*AA46/ABS(DPHI)                                            009650
      GO TO 2                                                                009660
    1 AA48=0                                                                 009670
    2 AA49R=MU*(S2R+RHOP2+RHO3*AA45R)-AP2*(SIN(LAMDA2-PHIS-DELP2)+MU*S2R009680
     1*COS(LAMDA2-PHIS-DELP2))                                               009690
      AA49F=-G2                                                              009700
      AA50=IZS*DOMZ+MU*(RHOF3*AA47+RHO3*AA43)                                009710
      AA51=-S7*AONE+BONE*MU1*S4-MU*RHO3*AA44                                 009720
      CG=COS(GAM)                                                            009730
      SG=SIN(GAM)                                                            009740
      AA52=CG*(IXX1*(DOMX*CG+DOMY*SG)+(IZZ1-IEE1)*OMZ*(-OMX*SG+OMY*CG)+I009750
     1XE1*(OMZ*(OMX*CG+OMY*SG)+(DOMX*SG-DOMY*CG))-IZX1*((OMX*CG+OMY*SG)*009760
     2(-OMX*SG+OMY*CG)+DOMZ)-IEZ1*((-OMX*SG+OMY*CG)**2-OMZ**2))-SG*(IEE1009770
     3*(-DOMX*SG+DOMY*CG)+(IXX1-IZZ1)*OMZ*(OMX*CG+OMY*SG)+IEZ1*((OMX*CG+009780
     4OMY*SG)*(-OMX*SG+OMY*CG)-DOMZ)-IXE1*((DOMX*CG+DOMY*SG)+OMZ*(-OMX*S009790
     5G+OMY*CG))-IZX1*(OMZ**2-(OMX*CG+OMY*SG)**2))                           009800
      AA53= ((-OMX*SG+OMY*CG)*((IXX1+IZZ1-IEE1)*CG+2.*IXE1*SG)+(OMX*C        009810
     1G+OMY*SG)*((IEE1-IXX1+IZZ1)*SG+2.*IXE1*CG)+2.*OMZ*(IXE1*CG+IZX1*SG009820
     2))                                                                     009830
      AA54= (IXE1*CG+IZX1*SG)                                                009840
      AA55= (-IZX1*CG+IEZ1*SG)                                               009850
      AA56=SG*(IXX1*(DOMX*CG+DOMY*SG)+(IZZ1-IEE1)*(-OMX*SG+OMY*CG)*OMZ+I009860
     1XE1*(OMZ*(OMX*CG+OMY*SG)-(-DOMX*SG+DOMY*CG))-IZX1*((OMX*CG+OMY*SG)009870
     2*(-OMX*SG+OMY*CG)+DOMZ)-IEZ1*((-OMX*SG+OMY*CG)**2-OMZ**2))+CG*(IEE009880
```

```
     31*(-DOMX*SG+DOMY*CG)+(IXX1-IZZ1)*(OMX*CG+OMY*SG)*OMZ+IEZ1*((OMX*CG009890
     4+OMY*SG)*(-OMX*SG+OMY*CG)-DOMZ)-IXE1*(DOMX*CG+DOMY*SG+OMZ*(-OMX*SG009900
     5+OMY*CG))-IZX1*(OMZ**2-(OMX*CG+OMY*SG)**2))                       009910
      AA57= ((-OMX*SG+OMY*CG)*((IXX1+IZZ1-IEE1)*SG-2.*IXE1*CG)+(OMX*C   009920
     1G+OMY*SG)*(2.*IXE1*SG+(IXX1-IZZ1-IEE1)*CG)+2.*OMZ*(IEZ1*SG-IZX1*CG009930
     2))                                                                009940
      AA58= (IEZ1*SG-IZX1*CG)                                           009950
      AA59=- (IZX1*SG+IEZ1*CG)                                          009960
      AA60=IZZ1*DOMZ+(IEE1-IXX1)*(OMX*CG+OMY*SG)*(-OMX*SG+OMY*CG)+IZX1*(009970
     1(-OMX*SG+OMY*CG)*OMZ-DOMX*CG-DOMY*SG)+IEZ1*(DOMX*SG-DOMY*CG-OMZ*(O009980
     2MX*CG+OMY*SG))-IXE1*((OMX*CG+OMY*SG)**2-(-OMX*SG+OMY*CG)**2)      009990
      AA61= IZZ1                                                        010000
      AA62=M1*RC1*(-OMY**2*CG+OMX*OMY*SG-OMZ**2*CG-DOMZ*SG)+M1*OX       010010
      AA63=-2.*M1*RC1*OMZ* CG                                           010020
      AA64=-M1*RC1* CG                                                  010030
      AA65=-M1*RC1* SG                                                  010040
      AA66R=COS(LAMDA1)-MU*S1R*SIN(LAMDA1)                              010050
      AA66F=SIN(PHI2P+ALPHP1)+MU*S1F*COS(PHI2P+ALPHP1)                  010060
      AA67=M1*RC1*(-OMX**2*SG+OMX*OMY*CG-OMZ**2*SG+DOMZ*CG)+M1*OY       010070
      AA68=-2.*M1*RC1* OMZ*SG                                           010080
      AA69=-M1*RC1* SG                                                  010090
      AA70=M1*RC1*CG                                                    010100
      AA71R=SIN(LAMDA1)+MU*S1R*COS(LAMDA1)                              010110
      AA71F=MU*S1F*SIN(PHI2P+ALPHP1)-COS(PHI2P+ALPHP1)                  010120
      RETURN                                                            010130
      END                                                               010140
```

```
      SUBROUTINE CTHREE (LU,LL,PHI1RC,PHITOT, M1,RC1,MU,OX,OY,OZ,AA52,  010150
     1AA53,AA54,AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65,A010160
     +A66R,AA66F,AA67,AA68,AA69,AA70,AA71R,AA71F,CC37,CC38,CC39,        010170
     +CC40,CC41R,CC41F,CC42,CC43,CC44,CC45,CC46R,CC46F,CC47,            010180
     +CC48,CC49,CC50,CC51R,CC51F,CC52,CC53,CC54,CC55,CC56R,CC56F)       010190
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,            010200
     +PHI2P,PHI1,PHI2,GAM                                               010210
      REAL LU,LL, M1,MU                                                 010220
      CG=COS(GAM)                                                       010230
      SG=SIN(GAM)                                                       010240
      CC37=ABS(-LL*AA62+MU*(AA52-LL*AA67)-AA56+M1*RC1*OZ*(MU*SG+CG))    010250
      CC38=ABS(-LL*AA63+MU*(AA53-LL*AA68)-AA57)                         010260
      CC39=ABS(-LL*AA64+MU*(AA54-LL*AA69)-AA58)                         010270
      CC40=ABS(-LL*AA65+MU*(AA55-LL*AA70)-AA59)                         010280
      CC41R=ABS(-LL*(AA66R+MU*AA71R))                                   010290
      CC41F=ABS(-LL*(AA66F+MU*AA71F))                                   010300
      CC42=ABS(-LL*AA67+MU*(AA56+LL*AA62)+AA52+M1*RC1*OZ*(SG-MU*CG))    010310
      CC43=ABS(-LL*AA68+MU*(LL*AA63+AA57)+AA53)                         010320
      CC44=ABS(-LL*AA69+MU*(LL*AA64+AA58)+AA54)                         010330
      CC45=ABS(-LL*AA70+MU*(LL*AA65+AA59)+AA55)                         010340
      CC46R=ABS(LL*(MU*AA66R-AA71R))                                    010350
      CC46F=ABS(LL*(MU*AA66F-AA71F))                                    010360
      CC47=ABS(LU*AA62+MU*(LU*AA67+AA52)-AA56+M1*RC1*OZ*(MU*SG+CG))     010370
      CC48=ABS(LU*AA63+MU*(LU*AA68+AA53)-AA57)                          010380
      CC49=ABS(LU*AA64+MU*(LU*AA69+AA54)-AA58)                          010390
      CC50=ABS(LU*AA65+MU*(LU*AA70+AA55)-AA59)                          010400
      CC51R=ABS(LU*(AA66R+MU*AA71R))                                    010410
      CC51F=ABS(LU*(AA66F+MU*AA71F))                                    010420
      CC52=ABS(LU*AA67+MU*(AA56-LU*AA62)+AA52+M1*RC1*OZ*(SG-MU*CG))     010430
      CC53=ABS(LU*AA68+MU*(AA57-LU*AA63)+AA53)                          010440
      CC54=ABS(LU*AA69+MU*(AA58-LU*AA64)+AA54)                          010450
      CC55=ABS(LU*AA70+MU*(AA59-LU*AA65)+AA55)                          010460
      CC56R=ABS(LU*(AA71R-MU*AA66R))                                    010470
      CC56F=ABS(LU*(AA71F-MU*AA66F))                                    010480
      RETURN                                                            010490
      END                                                               010500
```

```
      SUBROUTINE AFOUR(PHI,DPHI,CC37,CC38,CC39,CC40,                      010510
     +CC41R,CC41F,CC42,CC43,CC44,CC45,                                    010520
     +CC46R,CC46F,CC47,CC48,CC49,CC50,CC51R,CC51F,CC52,CC53,              010530
     +CC54,CC55,CC56R,CC56F,AA61,AA72,AA73,AA74,AA75,AA76,AA77,           010540
     +AA78R,AA78F,AA79R,AA79F,AA80,AA81,AA82,AA83,AA84RR,AA84FF,          010550
     +AA84RF,AA84FR,AA85RR,AA85FF,AA85RF,AA85FR,AA86,AA87RR,AA87FF,       010560
     +AA87RF,AA87FR,AA88RR,AA88FF,AA88RF,AA88FR,AA89,AA90,AA91,           010570
     +AA92,AA93)                                                          010580
      COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,      010590
     +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,   010600
     +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,    010610
     +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,        010620
     +GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,       010630
     +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,      010640
     +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,             010650
     +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2           010660
     +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2                                010670
     +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,           010680
     +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,                            010690
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F   010700
      COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8                          010710
      COMMON/DATA2/KX,KY,OX,OY,OZ,QX,QY,QZ                                010720
      COMMON/DATA4/I1R                                                    010730
      COMMON/DATA5/LU,LL,MU,MU1                                           010740
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,              010750
     +PHI2P,PHI1,PHI2,GAM                                                 010760
      REAL M1,M2,LU,LL,I1R,IX2,IY2,IZ2,MU,LAMDA1,LAMDA2                   010770
      CG=COS(GAM)                                                         010780
      SG=SIN(GAM)                                                         010790
      XX=(LU+LL)*(1.+MU**2)                                               010800
      AA72=ABS(M1*RC1*(OMZ*(OMX*CG+OMY*SG)+DOMX*SG-DOMY*CG)+M1*OZ)        010810
      AA73=ABS(2.*M1*RC1* (OMX*CG+OMY*SG))                                010820
      AA74=(CC37+CC42+CC47+CC52)/XX                                       010830
      AA75=(CC38+CC43+CC48+CC53)/XX                                       010840
      AA76=(CC39+CC44+CC49+CC54)/XX                                       010850
      AA77=(CC40+CC45+CC50+CC55)/XX                                       010860
      AA78R=(CC41R+CC46R+CC51R+CC56R)/XX                                  010870
      AA78F=(CC41F+CC46F+CC51F+CC56F)/XX                                  010880
      AA79R=AG1*(SIN(PHI1-DELG1-LAMDA1)-MU*S1R*COS(PHI1-DELG1-LAMDA1))    010890
     1-MU*(S1R*RHOG1+RHO1*AA78R)                                          010900
      AA79F=AG1*(COS(PHI1-DELG1-PHI2P-ALPHP1)+MU*S1F*SIN(PHI1-DELG1-      010910
     1PHI2P-ALPHP1))-MU*(S1F*RHOG1+RHO1*AA78F)                            010920
      AA80=MU*(RHOF1*AA72+RHO1*AA74)                                      010930
      AA81=ABS(MU)*(RHOF1*AA73+RHO1*AA75)                                 010940
      AA82=MU*RHO1*AA76                                                   010950
      AA83=ABS(MU)*RHO1*AA77                                              010960
      IF (DPHI*DPHI2.GE.0) I1R=AA61+AA83                                  010970
      IF (DPHI*DPHI2.LT.0) I1R=AA61-AA83                                  010980
      IF (I1R.LT.0) I1R=0                                                 010990
      AA84RR=-(COS(LAMDA2)+MU*S2R*SIN(LAMDA2))                            011000
      AA84FF=SIN(PHIS-ALPHP2)-MU*S2F*COS(PHIS-ALPHP2)                     011010
      AA84RF=AA84RR                                                       011020
      AA84FR=AA84FF                                                       011030
      AA85RR=COS(LAMDA1)-MU*S1R*SIN(LAMDA1)                               011040
      AA85FF=SIN(PHI2P+ALPHP1)+MU*S1F*COS(PHI2P+ALPHP1)                   011050
      AA85RF=AA85FF                                                       011060
      AA85FR=AA85RR                                                       011070
```

```
      AA86=-M2*QX
      AA87RR=-(SIN(LAMDA2)+MU*S2R*COS(LAMDA2))
      AA87FF=-(COS(PHIS-ALPHP2)+MU*S2F*SIN(PHIS-ALPHP2))
      AA87RF=AA87RR
      AA87FR=AA87FF
      AA88RR=SIN(LAMDA1)+MU*S1R*COS(LAMDA1)
      AA88FF=-COS(PHI2P+ALPHP1)+MU*S1F*SIN(PHI2P+ALPHP1)
      AA88RF=AA88FF
      AA88FR=AA88RR
      AA89=-M2*QY
      AA90=-(IX2*DOMX+OMY*OMZ*(IZ2-IY2))
      AA91=-IZ2 *OMY
      AA92=-(IY2*DOMY+OMX*OMZ*(IX2-IZ2))
      AA93=IZ2*OMX
      RETURN
      END
```

```
      SUBROUTINE CFOUR(AA84RR,AA84FF,AA84RF,AA84FR,AA85RR,              011240
     +AA85FF,AA85RF,AA85FR,AA86,AA87RR,AA87FF,AA87RF,AA87FR,AA88RR,     011250
     +AA88FF,AA88RF,AA88FR,AA89,AA90,AA91,AA92,AA93,CC57,CC58,          011260
     +CC59RR,CC59FF,CC59RF,CC59FR,CC60RR,CC60FF,CC60RF,CC60FR,CC61,     011270
     +CC62,CC63RR,CC63FF,CC63RF,CC63FR,CC64RR,CC64FF,CC64RF,            011280
     +CC64FR,CC65,CC66,CC67RR,CC67FF,CC67RF,CC67FR,CC68RR,CC68FF,       011290
     +CC68RF,CC68FR,CC69,CC70,CC71RR,CC71FF,CC71RF,CC71FR,CC72RR,       011300
     +CC72FF,CC72RF,CC72FR)                                             011310
      COMMON/DATA5/LU,LL,MU,MU1                                         011320
      REAL MU,LL,LU                                                     011330
      CC57=ABS(-LL*AA86+MU*(LL*AA89-AA90)-AA92)                         011340
      CC58=ABS(MU*AA91+AA93)                                            011350
      CC59RR=ABS(LL*(MU*AA87RR-AA84RR))                                 011360
      CC59FF=ABS(LL*(MU*AA87FF-AA84FF))                                 011370
      CC59RF=ABS(LL*(MU*AA87RF-AA84RF))                                 011380
      CC59FR=ABS(LL*(MU*AA87FR-AA84FR))                                 011390
      CC60RR=ABS(LL*(MU*AA88RR-AA85RR))                                 011400
      CC60FF=ABS(LL*(MU*AA88FF-AA85FF))                                 011410
      CC60RF=ABS(LL*(MU*AA88RF-AA85RF))                                 011420
      CC60FR=ABS(LL*(MU*AA88FR-AA85FR))                                 011430
      CC61=ABS(-LL*AA89-MU*(LL*AA86+AA92)+AA90)                         011440
      CC62=ABS(AA91-MU*AA93)                                            011450
      CC63RR=ABS(LL*(MU*AA84RR+AA87RR))                                 011460
      CC63FF=ABS(LL*(MU*AA84FF+AA87FF))                                 011470
      CC63RF=ABS(LL*(MU*AA84RF+AA87RF))                                 011480
      CC63FR=ABS(LL*(MU*AA84FR+AA87FR))                                 011490
      CC64RR=ABS(LL*(MU*AA85RR+AA88RR))                                 011500
      CC64FF=ABS(LL*(MU*AA85FF+AA88FF))                                 011510
      CC64RF=ABS(LL*(MU*AA85RF+AA88RF))                                 011520
      CC64FR=ABS(LL*(MU*AA85FR+AA88FR))                                 011530
      CC65=ABS(-MU*(LU*AA89+AA90)+LU*AA86-AA92)                         011540
      CC66=ABS(MU*AA91+AA93)                                            011550
      CC67RR=ABS(LU*(AA84RR-MU*AA87RR))                                 011560
      CC67FF=ABS(LU*(AA84FF-MU*AA87FF))                                 011570
      CC67RF=ABS(LU*(AA84RF-MU*AA87RF))                                 011580
      CC67FR=ABS(LU*(AA84FR-MU*AA87FR))                                 011590
      CC68RR=ABS(LU*(AA85RR-MU*AA88RR))                                 011600
      CC68FF=ABS(LU*(AA85FF-MU*AA88FF))                                 011610
      CC68RF=ABS(LU*(AA85RF-MU*AA88RF))                                 011620
      CC68FR=ABS(LU*(AA85FR-MU*AA88FR))                                 011630
      CC69=ABS(LU*AA89+MU*(LU*AA86-AA92)+AA90)                          011640
      CC70=ABS(AA91-MU*AA93)                                            011650
      CC71RR=ABS(LU*(MU*AA84RR+AA87RR))                                 011660
      CC71FF=ABS(LU*(MU*AA84FF+AA87FF))                                 011670
      CC71RF=ABS(LU*(MU*AA84RF+AA87RF))                                 011680
      CC71FR=ABS(LU*(MU*AA84FR+AA87FR))                                 011690
      CC72RR=ABS(LU*(MU*AA85RR+AA88RR))                                 011700
      CC72FF=ABS(LU*(MU*AA85FF+AA88FF))                                 011710
      CC72RF=ABS(LU*(MU*AA85RF+AA88RF))                                 011720
      CC72FR=ABS(LU*(MU*AA85FR+AA88FR))                                 011730
      RETURN                                                            011740
      END                                                               011750
```

```
      SUBROUTINE AFIVE(T,PHI,DPHI,PSI,DPSI,DELPHI,IPR)                  011760
      REAL M1,M2,M3,MP,IXXU,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,IXS,IYS011770
     1,IZS,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,MU,MU1,KX,KY,KZ,JX,JY,J        011780
     2Z,LX,LY,LZ,NX,NY,NZ,LU,LL,LAMBDA,NG1,NG2,NP2,NP3,IPR,I1R,         011790
     +LAMDA1,LAMDA2                                                     011800
      COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,    011810
     +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY, 011820
     +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,  011830
     +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,      011840
     +GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,     011850
     +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,    011860
     +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,           011870
     +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2         011880
     +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2                              011890
     +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,         011900
     +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,                          011910
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F 011920
      COMMON/DATA2/KX,KY,OX,OY,OZ,QX,QY,QZ                              011930
      COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8                        011940
      COMMON/DATA4/I1R                                                  011950
      COMMON/DATA5/LU,LL,MU,MU1                                         011960
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,            011970
     +PHI2P,PHI1,PHI2,GAM                                               011980
      COMMON/DATA7/DER2R,DER2F,DER1R,DER1F                              011990
      COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S      012000
      COMMON/DATA9/AA105,AA106,AA107,AA108,AA109,AA110,AA115,AA116,     012010
     +AA117,AA118,AA119,AA120,AA121,AA122,AA123,AA124,AA125,            012020
     +AA130,AA131,AA132                                                 012030
      COMMON/DATA10/AA9,AA29,AA30,AA31,AA32,AA48,AA49R,AA49F,AA50,AA51, 012040
     +AA60,AA79R,AA79F,AA80,AA81,AA82,AA99,AA100,AA101FR,AA101RR,       012050
     +AA101FF,AA101RF,AA102FR,AA102RR,AA102FF,AA102RF,AA103,AA104,      012060
     +AA111,AA112,AA113,AA114,AA126,AA127,AA128,AA129                   012070
      COMMON/DATA11/AA133,AA134,AA135,AA136,AA137,AA138,AA139,AA140,    012080
     +AA141,AA142,AA143,AA144,AA145,AA146,AA147,AA148,AA149,AA150,      012090
     +AA151,AA152,AA153,AA154,AA155,AA156,AA157,AA158,AA159,AA160,      012100
     +AA161,AA162,AA163,AA164,AA165,AA166,AA167,AA168,AA169,AA170,      012110
     +AA171,AA172,AA173,AA174,AA175,AA176,AA177                         012120
      COMMON/DATA12/X1,X2,X3,X4,X5,X6,X7,X8,X9,X10,X11,X12,Y1,Y2,Y3,Y4, 012130
     +Y5,Y6,Y7,Y8                                                       012140
      CALL ACCEL (RX,RY,RZ,GAMMA2,GAMMA3,GAMAPP,R1,R2,R3,R4,BETA3,GX,GY,012150
     1GZ,HX,HY,HZ,KX,KY,KZ,JX,JY,JZ,NX,NY,NZ,LX,LY,LZ,OX,OY,OZ,PX,PY,PZ,012160
     2QX,QY,QZ,T,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,DDZ)                        012170
      IF(DPHI.EQ.0)GO TO 1                                              012180
      MU=ABS(MU)*DPHI/ABS(DPHI)                                         012190
    1 CALL GKINEM(T,DPHI,PHDOT1,PHDOT2,X1,X2,X3,X4,X5,X6,               012200
     +X7,X8,X9,X10,X11,X12,Y1,Y2,Y3,Y4,Y5,Y6,Y7,Y8)                     012210
      IF (VST.NE.0)GO TO 3                                              012220
      S4=1.                                                             012230
      GO TO 4                                                           012240
    3 S4=VST/ABS(VST)                                                   012250
    4 IF (DPSI.NE.0) GO TO 5                                            012260
      S5=1.                                                             012270
      GO TO 6                                                           012280
    5 S5=DPSI/ABS(DPSI)                                                 012290
    6 IF (ALPHR.EQ.ALPHEN) S7=1.                                        012300
      IF (ALPHR.EQ.ALPHEX) S7=-1.                                       012310
      CALL AWON (S6,S7,ALPHR,BETA3,RCP,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,012320
```

```
     1MU1,S4,S5,PSI,PSIC,KX,KY,KZ,AA1,AA2,AA3                           012330
     2,AA4,AA5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,A012340
     3A18,AA19,AA20,AA21,AA22,AA23,PHITOT)                              012350
      CALL CWON (LU,LL,MU1,S5,MP,RCP,PSI,PSIC,KX,KY,KZ,AA1,AA2,AA3,AA4,A012360
     1A5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,AA18,AA012370
     219,AA20,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,CC10,CC012380
     311,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20)                  012390
      CALL ATWO(S7,CONE,DONE,DPSI,PSI,NX,NY,                            012400
     1NZ,AA16,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,CC10,CC012410
     211,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20,AA24,AA25,AA26,AA2012420
     +7,AA28,AA29,AA30,AA31,AA32,AA33,AA34R,AA34F,AA35,AA36,            012430
     +AA37R,AA37F,AA38,AA39,AA40,AA41,AA42,IPR)                         012440
      CALL CTWO(LU,LL,MU,S6,AA33,AA34R,AA34F,AA35,AA36,AA37R,           012450
     +AA37F,AA38,AA39,AA40,AA41,AA42,CC21,CC22,CC23R,CC23F,             012460
     +CC24,CC25,CC26,CC27R,CC27F,CC28,CC29,CC30,CC31R,CC31F,            012470
     +CC32,CC33,CC34,CC35R,CC35F,CC36)                                  012480
      CALL ATHREE (S7,DPHI,AONE,BONE,NZ                                 012490
     +,CC21,CC22,CC23R,CC23F,CC24,CC25,CC26,CC27R,CC27F,CC28,           012500
     +CC29,CC30,CC31R,CC31F,CC32,CC33,CC34,CC35R,CC35F,CC36,AA43,AA44,  012510
     +AA45R,AA45F,AA46,AA47,AA48,AA49R,AA49F,AA50,AA51,AA52,AA53,AA54,  012520
     +AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65            012530
     +,AA66R,AA66F,AA67,AA68,AA69,AA70,AA71R,AA71F)                     012540
      CALL CTHREE (LU,LL,PHI1RC,PHITOT, M1,RC1,MU,DX,DY,DZ,AA52,        012550
     1AA53,AA54,AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65,A012560
     +A66R,AA66F,AA67,AA68,AA69,AA70,AA71R,AA71F,CC37,CC38,CC39,        012570
     +CC40,CC41R,CC41F,CC42,CC43,CC44,CC45,CC46R,CC46F,CC47,            012580
     +CC48,CC49,CC50,CC51R,CC51F,CC52,CC53,CC54,CC55,CC56R,CC56F)       012590
      CALL AFOUR (PHI,DPHI,                                             012600
     +CC37,CC38,CC39,CC40,CC41R,CC41F,CC42,CC43,CC44,CC45,              012610
     +CC46R,CC46F,CC47,CC48,CC49,CC50,CC51R,CC51F,CC52,CC53,            012620
     +CC54,CC55,CC56R,CC56F,AA61,AA72,AA73,AA74,AA75,AA76,AA77,         012630
     +AA78R,AA78F,AA79R,AA79F,AA80,AA81,AA82,AA83,AA84RR,AA84FF,        012640
     +AA84RF,AA84FR,AA85RR,AA85FF,AA85RF,AA85FR,AA86,AA87RR,AA87FF,     012650
     +AA87RF,AA87FR,AA88RR,AA88FF,AA88RF,AA88FR,AA89,AA90,AA91,         012660
     +AA92,AA93)                                                        012670
      CALL CFOUR(AA84RR,AA84FF,AA84RF,AA84FR,AA85RR,                    012680
     +AA85FF,AA85RF,AA85FR,AA86,AA87RR,AA87FF,AA87RF,AA87FR,AA88RR,     012690
     +AA88FF,AA88RF,AA88FR,AA89,AA90,AA91,AA92,AA93,CC57,CC58,          012700
     +CC59RR,CC59FF,CC59RF,CC59FR,CC60RR,CC60FF,CC60RF,CC60FR,CC61,     012710
     +CC62,CC63RR,CC63FF,CC63RF,CC63FR,CC64RR,CC64FF,CC64RF,            012720
     +CC64FR,CC65,CC66,CC67RR,CC67FF,CC67RF,CC67FR,CC68RR,CC68FF,       012730
     +CC68RF,CC68FR,CC69,CC70,CC71RR,CC71FF,CC71RF,CC71FR,CC72RR,       012740
     +CC72FF,CC72RF,CC72FR)                                             012750
      XX=(LU+LL)*(1.+MU**2)                                             012760
      SG=SIN(GAM)                                                       012770
      CG=COS(GAM)                                                       012780
      AA94=(CC57+CC61+CC65+CC69)/XX                                     012790
      AA95=(CC58+CC62+CC66+CC70)/XX                                     012800
      AA96RR=(CC59RR+CC63RR+CC67RR+CC71RR)/XX                           012810
      AA96FF=(CC59FF+CC63FF+CC67FF+CC71FF)/XX                           012820
      AA96RF=(CC59RF+CC63RF+CC67RF+CC71RF)/XX                           012830
      AA96FR=(CC59FR+CC63FR+CC67FR+CC71FR)/XX                           012840
      AA97RR=(CC60RR+CC64RR+CC68RR+CC72RR)/XX                           012850
      AA97FF=(CC60FF+CC64FF+CC68FF+CC72FF)/XX                           012860
      AA97RF=(CC60RF+CC64RF+CC68RF+CC72RF)/XX                           012870
      AA97FR=(CC60FR+CC64FR+CC68FR+CC72FR)/XX                           012880
      AA98=ABS(M2*QZ)                                                   012890
```

```
      AA99=IZ2+DOMZ                                                     012900
      AA100=IZ2                                                         012910
      AA101RR=AG2*(SIN(PHI2+DELG2-LAMDA2)-MU*S2R*COS(PHI2+DELG2-LAMDA2))012920
     1-MU*(S2R*RHOG2-RHO2*AA96RR)                                       012930
      AA101FF=AG2*(-COS(PHI2+DELG2-PHIS+ALPHP2)+MU*S2F*SIN(PHI2+DELG2   012940
     1-PHIS+ALPHP2))+MU*(RHO2*AA96FF+S2F*RHOG2)                         012950
      AA101RF=AG2*(SIN(PHI2+DELG2-LAMDA2)-MU*S2R*COS(PHI2+DELG2-LAMDA2))012960
     1-MU*(S2R*RHOG2-RHO2*AA96RF)                                       012970
      AA101FR=AG2*(-COS(PHI2+DELG2-PHIS+ALPHP2)+MU*S2F*SIN(PHI2+DELG2   012980
     1-PHIS+ALPHP2))+MU*(S2F*RHOG2+RHO2*AA96FR)                         012990
      AA102RR=AP1*(SIN(PHI2P-DELP1-LAMDA1)-MU*S1R*COS(PHI2P-DELP1-LAMDA1013000
     1))+MU*(S1R*RHOP1-RHO2*AA97RR)                                     013010
      AA102FF=G1-MU*RHO2*AA97FF                                         013020
      AA102RF=G1-MU*RHO2*AA97RF                                         013030
      AA102FR=AP1*(SIN(PHI2P-DELP1-LAMDA1)-MU*S1R*COS(PHI2P-DELP1-LAMDA1013040
     +))+MU*(S1R*RHOP1-RHO2*AA97FR)                                     013050
      AA103=MU*(RHOF2*AA98+RHO2*AA94)                                   013060
      AA104=ABS(MU)*RHO2*AA95                                           013070
      AA105=AA51*IPR*U-AA29*IZS-(AA29*AA49R*AA100*Y5)/AA101RR-(AA29*    013080
     1AA49R*AA102RR*I1R*Y1*Y5)/(AA79R*AA101RR)                          013090
      AA106=AA51*(AA32*U**2+IPR*V)-AA29*AA48-(AA29*AA49R*AA102RR*I1R)/( 013100
     1AA79R*AA101RR)*(Y1*Y6+Y2*DER2R**2)-(AA29*AA49R*AA82*AA102RR*DER1R 013110
     2*DER1R*DER2R**2)/(AA79R*AA101RR)-(AA29*AA49R*AA100*Y6)/AA101RR    013120
      AA107=AA51*AA31*U-(AA29*AA49R*AA81*AA102RR*DER1R*DER2R)/(AA79R*   013130
     1AA101RR)-(AA29*AA49R*AA104*DER2R)/AA101RR                         013140
      AA108=AA29*AA50-AA51*(AA9+AA30)+(AA29*AA49R)/AA101RR*(AA102RR*    013150
     1(AA80+AA60)/AA79R-AA103+AA99)                                     013160
      AA109=-(AA29*AA49R*AA102RR*M1*RC1)/(AA79R*AA101RR)                013170
      AA110=AA51*MP*RCP                                                 013180
      AA111=AA102RR*I1R*Y1*Y5/AA79R+AA100*Y5                            013190
      AA112=AA102RR/AA79R*(I1R*(Y1*Y6+Y2*DER2R**2)+AA82*DER1R**2*DER2R* 013200
     1DER2R)+AA100*Y6                                                   013210
      AA113=AA102RR*AA81*DER1R*DER2R/AA79R+AA104*DER2R                  013220
      AA114=AA102RR/AA79R*(AA80+AA60-M1*RC1*(OX*SG-OY*CG))-AA103+AA99   013230
      AA115=I1R*Y1*Y5                                                   013240
      AA116=I1R*(Y1*Y6+Y2*DER2R**2)+AA82*DER1R**2*DER2R**2              013250
      AA117=AA81*DER1R*DER2R                                            013260
      AA118=AA80+AA60-M1*RC1*(OX*SG-OY*CG)                              013270
      AA119=AA9+AA30                                                    013280
      AA120=AA51*IPR*U-AA29*IZS- AA100*AA29*AA49F*Y7/AA101FF            013290
     1-AA29*AA49F*AA102FF*I1R*Y3*Y7/(AA101FF*AA79F)                     013300
      AA121=AA51*(AA32*U**2+IPR*V)-AA29*AA48- AA82*AA29*AA49F*AA102FF   013310
     1*DER1F**2*DER2F**2/(AA101FF*AA79F)- AA100*AA29*AA49F*Y8/AA101FF   013320
     2-AA29*AA49F*AA102FF*I1R*(Y3*Y8+Y4*DER2F**2)/(AA101FF*AA79F)       013330
      AA122=AA51*AA31*U-AA81*AA29*AA49F*AA102FF*DER1F*DER2F/(AA101F     013340
     1F*AA79F)-AA104*AA29*AA49F*DER2F/AA101FF                           013350
      AA123=AA29*AA50-AA51*(AA9+AA30)+AA29*AA49F*(AA102FF*(AA80+AA60)/  013360
     1AA79F-AA103+AA99)/AA101FF                                         013370
      AA124=-AA29*AA49F*AA102FF*M1*RC1/(AA101FF*AA79F)                  013380
      AA125=AA51*MP*RCP                                                 013390
      AA126=AA102FF*I1R*Y3*Y7/AA79F+AA100*Y7                            013400
      AA127=AA102FF*(I1R*(Y3*Y8+Y4*DER2F**2)+AA82*DER1F**2*DER2F**2)/   013410
     1AA79F+AA100*Y8                                                    013420
      AA128=AA102FF*AA81*DER1F*DER2F/AA79F+AA104*DER2F                  013430
      AA129=AA102FF*(AA80+AA60-M1*RC1*(OX*SG-OY*CG))/AA79F-AA103+AA99   013440
      AA130=I1R*Y3*Y7                                                   013450
      AA131=I1R*(Y3*Y8+Y4*DER2F**2)+AA82*DER1F**2*DER2F**2              013460
```

```
      AA132=AA81*DER1F*DER2F
      RETURN
      END
```

```
      SUBROUTINE ASIX(T,PHI,DPHI,PSI,DPSI,DELPHI,IPR)                   013500
      REAL M1,M2,M3,MP,IXXU,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,IXS,IYS013510
     1,IZS,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,MU,MU1,KX,KY,KZ,JX,JY,J        013520
     2Z,LX,LY,LZ,NX,NY,NZ,LU,LL,LAMBDA,NG1,NG2,NP2,NP3,IPR,I1R,          013530
     +LAMDA1,LAMDA2                                                     013540
      COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,    013550
     +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY, 013560
     +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,  013570
     +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,      013580
     +GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,     013590
     +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,    013600
     +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,           013610
     +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2         013620
     +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2                              013630
     +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,         013640
     +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,                          013650
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F 013660
      COMMON/DATA2/KX,KY,OX,OY,OZ,QX,QY,QZ                              013670
      COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8                        013680
      COMMON/DATA4/I1R                                                  013690
      COMMON/DATA5/LU,LL,MU,MU1                                         013700
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,            013710
     +PHI2P,PHI1,PHI2,GAM                                               013720
      COMMON/DATA7/DER2R,DER2F,DER1R,DER1F                              013730
      COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S      013740
      COMMON/DATA9/AA105,AA106,AA107,AA108,AA109,AA110,AA115,AA116,     013750
     +AA117,AA118,AA119,AA120,AA121,AA122,AA123,AA124,AA125,            013760
     +AA130,AA131,AA132                                                 013770
      COMMON/DATA10/AA9,AA29,AA30,AA31,AA32,AA48,AA49R,AA49F,AA50,AA51, 013780
     +AA60,AA79R,AA79F,AA80,AA81,AA82,AA99,AA100,AA101FR,AA101RR,       013790
     +AA101FF,AA101RF,AA102FR,AA102RR,AA102FF,AA102RF,AA103,AA104,      013800
     +AA111,AA112,AA113,AA114,AA126,AA127,AA128,AA129                   013810
      COMMON/DATA11/AA133,AA134,AA135,AA136,AA137,AA138,AA139,AA140,    013820
     +AA141,AA142,AA143,AA144,AA145,AA146,AA147,AA148,AA149,AA150,      013830
     +AA151,AA152,AA153,AA154,AA155,AA156,AA157,AA158,AA159,AA160,      013840
     +AA161,AA162,AA163,AA164,AA165,AA166,AA167,AA168,AA169,AA170,      013850
     +AA171,AA172,AA173,AA174,AA175,AA176,AA177                         013860
      COMMON/DATA12/X1,X2,X3,X4,X5,X6,X7,X8,X9,X10,X11,X12,Y1,Y2,Y3,Y4, 013870
     +Y5,Y6,Y7,Y8                                                       013880
      CALL ACCEL (RX,RY,RZ,GAMMA2,GAMMA3,GAMAPP,R1,R2,R3,R4,BETA3,GX,GY,013890
     1GZ,HX,HY,HZ,KX,KY,KZ,JX,JY,JZ,NX,NY,NZ,LX,LY,LZ,OX,OY,OZ,PX,PY,PZ,013900
     2QX,QY,QZ,T,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,DDZ)                        013910
      IF(DPHI.EQ.O)GO TO 1                                              013920
      MU=ABS(MU)*DPHI/ABS(DPHI)                                         013930
    1 CALL GKINEM(T,DPHI,PHDOT1,PHDOT2,X1,X2,X3,X4,X5,X6,               013940
     +X7,X8,X9,X10,X11,X12,Y1,Y2,Y3,Y4,Y5,Y6,Y7,Y8)                     013950
      IF (VST.NE.O)GO TO 3                                              013960
      S4=1.                                                             013970
      GO TO 4                                                           013980
    3 S4=VST/ABS(VST)                                                   013990
    4 IF (DPSI.NE.O) GO TO 5                                            014000
      S5=1.                                                             014010
      GO TO 6                                                           014020
    5 S5=DPSI/ABS(DPSI)                                                 014030
    6 IF (ALPHR.EQ.ALPHEN) S7=1.                                        014040
      IF (ALPHR.EQ.ALPHEX) S7=-1.                                       014050
      CALL AWON (S6,S7,ALPHR,BETA3,RCP,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,014060
```

```
     1MU1,S4,S5,PSI,PSIC,KX,KY,KZ,AA1,AA2,AA3                        014070
     2,AA4,AA5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,A014080
     3A18,AA19,AA20,AA21,AA22,AA23,PHITOT)                           014090
      CALL CWON (LU,LL,MU1,S5,MP,RCP,PSI,PSIC,KX,KY,KZ,AA1,AA2,AA3,AA4,A014100
     1A5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,AA18,AA014110
     219,AA20,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,CC10,CC014120
     311,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20)               014130
      CALL ATWO(S7,CONE,DONE,DPSI,PSI,NX,NY,                         014140
     1NZ,AA16,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,CC10,CC014150
     211,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20,AA24,AA25,AA26,AA2014160
     +7,AA28,AA29,AA30,AA31,AA32,AA33,AA34R,AA34F,AA35,AA36,         014170
     +AA37R,AA37F,AA38,AA39,AA40,AA41,AA42,IPR)                      014180
      CALL CTWO(LU,LL,MU,S6,AA33,AA34R,AA34F,AA35,AA36,AA37R,        014190
     +AA37F,AA38,AA39,AA40,AA41,AA42,CC21,CC22,CC23R,CC23F,          014200
     +CC24,CC25,CC26,CC27R,CC27F,CC28,CC29,CC30,CC31R,CC31F,         014210
     +CC32,CC33,CC34,CC35R,CC35F,CC36)                               014220
      CALL ATHREE (S7,DPHI,AONE,BONE,NZ                              014230
     +,CC21,CC22,CC23R,CC23F,CC24,CC25,CC26,CC27R,CC27F,CC28,        014240
     +CC29,CC30,CC31R,CC31F,CC32,CC33,CC34,CC35R,CC35F,CC36,AA43,AA44, 014250
     +AA45R,AA45F,AA46,AA47,AA48,AA49R,AA49F,AA50,AA51,AA52,AA53,AA54, 014260
     +AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65         014270
     +,AA66R,AA66F,AA67,AA68,AA69,AA70,AA71R,AA71F)                  014280
      CALL CTHREE (LU,LL,PHI1RC,PHITOT, M1,RC1,MU,OX,OY,OZ,AA52,     014290
     1AA53,AA54,AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65,A014300
     +A66R,AA66F,AA67,AA68,AA69,AA70,AA71R,AA71F,CC37,CC38,CC39,     014310
     +CC40,CC41R,CC41F,CC42,CC43,CC44,CC45,CC46R,CC46F,CC47,         014320
     +CC48,CC49,CC50,CC51R,CC51F,CC52,CC53,CC54,CC55,CC56R,CC56F)    014330
      CALL AFOUR (PHI,DPHI,                                          014340
     +CC37,CC38,CC39,CC40,CC41R,CC41F,CC42,CC43,CC44,CC45,           014350
     +CC46R,CC46F,CC47,CC48,CC49,CC50,CC51R,CC51F,CC52,CC53,         014360
     +CC54,CC55,CC56R,CC56F,AA61,AA72,AA73,AA74,AA75,AA76,AA77,      014370
     +AA78R,AA78F,AA79R,AA79F,AA80,AA81,AA82,AA83,AA84RR,AA84FF,     014380
     +AA84RF,AA84FR,AA85RR,AA85FF,AA85RF,AA85FR,AA86,AA87RR,AA87FF,  014390
     +AA87RF,AA87FR,AA88RR,AA88FF,AA88RF,AA88FR,AA89,AA90,AA91,      014400
     +AA92,AA93)                                                     014410
      CALL CFOUR(AA84RR,AA84FF,AA84RF,AA84FR,AA85RR,                 014420
     +AA85FF,AA85RF,AA85FR,AA86,AA87RR,AA87FF,AA87RF,AA87FR,AA88RR,  014430
     +AA88FF,AA88RF,AA88FR,AA89,AA90,AA91,AA92,AA93,CC57,CC58,       014440
     +CC59RR,CC59FF,CC59RF,CC59FR,CC60RR,CC60FF,CC60RF,CC60FR,CC61,  014450
     +CC62,CC63RR,CC63FF,CC63RF,CC63FR,CC64RR,CC64FF,CC64RF,         014460
     +CC64FR,CC65,CC66,CC67RR,CC67FF,CC67RF,CC67FR,CC68RR,CC68FF,    014470
     +CC68RF,CC68FR,CC69,CC70,CC71RR,CC71FF,CC71RF,CC71FR,CC72RR,    014480
     +CC72FF,CC72RF,CC72FR)                                          014490
      XX=(LU+LL)*(1.+MU**2)                                          014500
      SG=SIN(GAM)                                                    014510
      CG=COS(GAM)                                                    014520
      AA133=AA80+AA60-M1*RC1*(OX*SG-OY*CG)                           014530
      AA134=AA51*IPR*U-AA29*IZS- AA29*AA49R*AA102RF*I1R*Y3*Y5 /(AA79F* 014540
     1AA101RF)-AA29*AA49R*AA100*Y5/AA101RF                           014550
      AA135=AA51*(AA32*U*U+IPR*V)-AA29*AA48- AA29*AA49R*AA102RF*I1R* 014560
     1(Y3*Y6+Y4*DER2R**2) /(AA79F*AA101RF)-AA29*AA49R*AA82*AA102RF*  014570
     2DER2R**2*DER1F**2/(AA79F*AA101RF)-AA29*AA49R*AA100*Y6/AA101RF  014580
      AA136=AA51*AA31*U- AA29*AA49R*AA81*AA102RF*DER2R*DER1F/(AA79F* 014590
     1AA101RF)-AA29*AA49R*AA104*DER2R/AA101RF                        014600
      AA137=AA29*AA50-AA51*(AA9+AA30)+AA29*AA49R*(AA102RF*(AA80+AA60)/ 014610
     1AA79F-AA103+AA99)/AA101RF                                      014620
      AA138=-AA29*AA49R*AA102RF*M1*RC1/(AA10[illegible]A79F)         014630
```

```
      AA139=AA51*MP*RCP
      AA140=AA102RF*I1R*Y3*Y5/AA79F+AA100*Y5
      AA141=AA102RF*(I1R*(Y3*Y6+Y4*DER2R**2)+AA82*DER2R**2*DER1F**2)/
     1AA79F+AA100*Y6
      AA142=AA102RF*AA81*DER2R*DER1F/AA79F+AA104*DER2R
      AA143=AA102RF*(AA80+AA60-M1*RC1*(OX*SG-OY*CG))/AA79F-AA103+AA99
      AA144=I1R*Y3*Y5
      AA145=I1R*(Y3*Y6+Y4*DER2R**2)+AA82*DER1F**2*DER2R**2
      AA146=AA81*DER1F*DER2R
      AA147=AA80+AA60-M1*RC1*(OX*SG-OY*CG)
      AA148=AA51*IPR*U-AA29*IZS-(AA29*AA49F*(AA102FR*I1R*Y1*Y7/AA79R+
     1AA100*Y7))/AA101FR
      AA149=AA51*(AA32*U*U+IPR*V)-AA29*AA48-(AA29*AA49F*(AA102FR*(I1R*
     1(Y1*Y8+Y2*DER2F**2)+AA82*DER1R**2*DER2F**2)/AA79R+AA100*Y8))/
     1AA101FR
      AA150=AA51*AA31*U-(AA29*AA49F*(AA102FR*AA81*DER1R*DER2F/AA79R+
     1AA104*DER2F))/AA101FR
      AA151=AA29*AA50-AA51*(AA9+AA30)+(AA29*AA49F*(AA102FR*(AA80+AA60)/
     1AA79R-AA103+AA99))/AA101FR
      AA152=-AA29*AA49F*AA102FR*M1*RC1/(AA101FR*AA79R)
      AA153=AA51*MP*RCP
      AA154=AA102FR*I1R*Y1*Y7/AA79R+AA100*Y7
      AA155=AA102FR*(I1R*(Y1*Y8+Y2*DER2F**2)+AA82*DER1R**2*DER2F**2)/
     1AA79R+AA100*Y8
      AA156=AA102FR*AA81*DER1R*DER2F/AA79R+AA104*DER2F
      AA157=AA102FR*(AA80+AA60-M1*RC1*(OX*SG-OY*CG))/AA79R-AA103+AA99
      AA158=I1R*Y1*Y7
      AA159=I1R*(Y1*Y8+Y2*DER2F**2+AA82*DER1R**2*DER2F**2)
      AA160=AA81*DER1R*DER2F
      AA161=AA80+AA60-M1*RC1*(OX*SG-OY*CG)
      AA162=IZS+AA49R*AA111/AA101RR
      AA163=AA48+AA49R*AA112/AA101RR
      AA164=AA49R*AA113/AA101RR
      AA165=AA50+AA49R*AA114/AA101RR
      AA166=IZS+AA49F*AA126/AA101FF
      AA167=AA48+AA49F*AA127/AA101FF
      AA168=AA49F*AA128/AA101FF
      AA169=AA49F*AA129/AA101FF+AA50
      AA170=IZS+AA49R*AA140/AA101RF
      AA171=AA48+AA49R*AA141/AA101RF
      AA172=AA49R*AA142/AA101RF
      AA173=AA49R*AA143/AA101RF+AA50
      AA174=IZS+AA49F*AA154/AA101FR
      AA175=AA48+AA49F*AA155/AA101FR
      AA176=AA49F*AA156/AA101FR
      AA177=AA49F*AA157/AA101FR+AA50
      RETURN
      END
```

```
      SUBROUTINE AERO(RPM,T,DDZ)                                        015120
      COMMON/DATA3/OMX,OMY,OMZ,DOMX,DOMY,DOMZ,S8                        015130
      REAL KP,KN                                                        015140
      KP=100.                                                           015150
      KN=20.                                                            015160
      PI=3.14159                                                        015170
      Z=PI/180.                                                         015180
      THETIN=15.*Z                                                      015190
      DPHIE=RPM*2.*PI/60.                                               015200
      PHIE=DPHIE*T                                                      015210
      DPSIE=DPHIE/KP                                                    015220
      PSIE=DPSIE*T                                                      015230
      TV=5.*Z                                                           015240
      THET=THETIN+TV*SIN(KN*DPSIE*T)                                    015250
      DTHET=TV*KN*DPSIE*COS(KN*DPSIE*T)                                 015260
      DDZ=-386.*10.*S8                                                  015270
      DTHET2=-TV*KN**2*DPSIE**2*SIN(KN*DPSIE*T)                         015280
      OMX=DTHET*COS(PHIE)+DPSIE*SIN(THET)*SIN(PHIE)                     015290
      OMY=-DTHET*SIN(PHIE)+DPSIE*SIN(THET)*COS(PHIE)                    015300
      OMY=OMY*S8                                                        015305
      OMZ=DPHIE+DPSIE*COS(THET)                                         015310
      OMZ=OMZ*S8                                                        015315
      DOMX=DTHET2*COS(PHIE)-DTHET*DPHIE*SIN(PHIE)+DPSIE*DTHET*COS(THET)*015320
     1SIN(PHIE)+DPSIE*DPHIE*SIN(THET)*COS(PHIE)                         015330
      DOMY=-DTHET2*SIN(PHIE)-DTHET*DPHIE*COS(PHIE)+DPSIE*DTHET*COS(THET)015340
     1*COS(PHIE)-DPSIE*DPHIE*SIN(THET)*SIN(PHIE)                        015350
      DOMY=DOMY*S8                                                      015355
      DOMZ=-DPSIE*DTHET*SIN(THET)                                       015360
      DOMZ=DOMZ*S8                                                      015365
      RETURN                                                            015370
      END                                                               015380
```

```
      SUBROUTINE KINEM(A,B,ALPHR,PHI,C,PSI,DPSI)                        015390
      COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S      015400
      DIMENSION PHI(2)                                                  015410
      PI=3.14159                                                        015420
      CAPA=A*COS(ALPHR)+B*COS(PHI(1)-ALPHR)                             015430
      CAPB=A*SIN(ALPHR)-B*SIN(PHI(1)-ALPHR)                             015440
      CAPC=C*SIN(ALPHR)                                                 015450
      PSI=2.*ATAN2((CAPA-SQRT(CAPA**2+CAPB**2-CAPC**2)),(CAPB+CAPC))    015460
      IF (PSI.LT.O.) PSI=2.*PI+PSI                                      015470
      G=(B*SIN(PHI(1))-C*SIN(PSI))/SIN(PSI+ALPHR)                       015480
      P=B*COS(PHI(1)-ALPHR-PSI)                                         015490
      Q=A*COS(PSI+ALPHR)+B*COS(PHI(1)-ALPHR-PSI)                        015500
      U=P/Q                                                             015510
      V=1./Q**3*(A*P**2*SIN(PSI+ALPHR)-B*(P-Q)**2*SIN(PHI(1)-ALPHR-PSI))015520
      AONE=B*COS(PHI(1)-PSI-ALPHR)                                      015530
      BONE=B*SIN(PHI(1)-PSI-ALPHR)                                      015540
      CONE=-C*SIN(ALPHR)                                                015550
      DONE=C*COS(ALPHR)+G                                               015560
      DPSI=U*PHI(2)                                                     015570
      VST=-PHI(2)*B*SIN(PHI(1)-PSI-ALPHR)-DPSI*C*SIN(ALPHR)             015580
      RETURN                                                            015590
      END                                                               015600
```

```
      SUBROUTINE GKINEM(T,DPHI,PHDOT1,PHDOT2,X1,X2,X3,X4,X5,X6,           015610
     +X7,X8,X9,X10,X11,X12,Y1,Y2,Y3,Y4,Y5,Y6,Y7,Y8)                      015620
      COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,      015630
     +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,  015640
     +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,   015650
     +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,       015660
     +GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,      015670
     +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,     015680
     +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,            015690
     +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2          015700
     +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2                               015710
     +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,          015720
     +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,                           015730
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F 015740
      COMMON/DATA5/LU,LL,MU,MU1                                          015750
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,             015760
     +PHI2P,PHI1,PHI2,GAM                                                015770
      COMMON/DATA7/DER2R,DER2F,DER1R,DER1F                               015780
      COMMON/DATA13/PHISI,PHISFF,PHIST,PH2PI,PH2PFF,PH2PT                015790
      REAL LAMDA1,LAMDA2,L1,L2                                           015800
C                                                                        015810
C     MESH 2                                                             015820
C                                                                        015830
      IF(PHIS.GE.PHISFF)PHIS=PHISI                                       015840
      IF(PHIS.GE.PHIST)GO TO 35                                          015850
      D2R=-2.*AP2*AG2*SIN(PHIS+DELP2-DELG2)-2.*AG2*B2*SIN(BETA2-DELG2)  015860
      E2R=-2.*AP2*AG2*COS(PHIS+DELP2-DELG2)-2.*AG2*B2*COS(BETA2-DELG2)  015870
      F2R=L2**2-AG2**2-AP2**2-B2**2-2.*AP2*B2*COS(PHIS+DELP2-BETA2)     015880
      ROOT2R=D2R**2+E2R**2-F2R**2                                        015890
      Y2R=D2R+RSGN2R*SQRT(ROOT2R)                                        015900
      X2R=E2R+F2R                                                        015910
      PHI2=2.*ATAN2(Y2R,X2R)                                             015920
      IF(PHI2.LT.O)PHI2=PHI2+2.*PI                                       015930
      PHI2D=PHI2/ZZ                                                      015940
      SLAM2=(B2*SIN(BETA2)+AP2*SIN(PHIS+DELP2)-AG2*SIN(PHI2+DELG2))/L2  015950
      CLAM2=(B2*COS(BETA2)+AP2*COS(PHIS+DELP2)-AG2*COS(PHI2+DELG2))/L2  015960
      LAMDA2=ATAN2(SLAM2,CLAM2)                                          015970
      D2RD=-2.*AP2*AG2*COS(PHIS+DELP2-DELG2)                             015980
      E2RD=2.*AP2*AG2*SIN(PHIS+DELP2-DELG2)                              015990
      F2RD=2.*AP2*B2*SIN(PHIS+DELP2-BETA2)                               016000
      DER2R=(F2RD-D2RD*SIN(PHI2)-E2RD*COS(PHI2))/(D2R*COS(PHI2)-E2R*    016010
     1SIN(PHI2))                                                         016020
      PHDOT2=DPHI*DER2R                                                  016030
      VST2R= PHDOT2*(AG2*COS(PHI2+DELG2-LAMDA2)+RHOG2)-DPHI*(AP2*       016040
     1COS(PHIS+DELP2-LAMDA2)-RHOP2)                                      016050
      IF(VST2R.NE.O)GO TO 100                                            016060
      S2R=1.                                                             016070
      GO TO 101                                                          016080
  100 S2R=VST2R/ABS(VST2R)                                               016090
  101 D2RDD=2.*AP2*AG2*SIN(PHIS+DELP2-DELG2)                             016100
      E2RDD=2.*AP2*AG2*COS(PHIS+DELP2-DELG2)                             016110
      F2RDD=2.*AP2*B2*COS(PHIS+DELP2-BETA2)                              016120
      X7=1./(D2R*COS(PHI2)-E2R*SIN(PHI2))                                016130
      X8=F2RD-D2RD*SIN(PHI2)-E2RD*COS(PHI2)                              016140
      X9=F2RDD-D2RDD*SIN(PHI2)-E2RDD*COS(PHI2)+DER2R*(-2.*D2RD*COS(PHI2)016150
     1+2.*E2RD*SIN(PHI2))+DER2R**2*(D2R*SIN(PHI2)+E2R*COS(PHI2))        016160
      Y5=X7*X8                                                           016170
```

```
      Y6=X7*X9                                                          016180
      GO TO 36                                                          016190
   35 D2F=-AG2*COS(PHIS-ALPHP2-DELG2)                                   016200
      E2F=AG2*SIN(PHIS-ALPHP2-DELG2)                                    016210
      F2F=RHOG2+B2*SIN(PHIS-ALPHP2-BETA2)                               016220
      ROOT2F=D2F**2+E2F**2-F2F**2                                       016230
      Y2F=D2F+RSGN2F*SQRT(ROOT2F)                                       016240
      X2F=E2F+F2F                                                       016250
      PHI2=2.*ATAN2(Y2F,X2F)                                            016260
      IF(PHI2.LT.0)PHI2=PHI2+2.*PI                                      016270
      PHI2D=PHI2/ZZ                                                     016280
      G2=(AG2*SIN(PHI2+DELG2)+RHOG2*COS(PHIS-ALPHP2)-B2*SIN(BETA2))/    016290
     1SIN(PHIS-ALPHP2)                                                  016300
      D2FD=AG2*SIN(PHIS-ALPHP2-DELG2)                                   016310
      E2FD=AG2*COS(PHIS-ALPHP2-DELG2)                                   016320
      F2FD=B2*COS(PHIS-ALPHP2-BETA2)                                    016330
      DER2F=(F2FD-D2FD*SIN(PHI2)-E2FD*COS(PHI2))/(D2F*COS(PHI2)-E2F*    016340
     1SIN(PHI2))                                                        016350
      PHDOT2=DPHI*DER2F                                                 016360
      VST2F=PHDOT2*(AG2*SIN(PHIS-ALPHP2-PHI2-DELG2)-RHOG2)              016370
      IF(VST2F.NE.0)GO TO 102                                           016380
      S2F=1.                                                            016390
      GO TO 103                                                         016400
  102 S2F=VST2F/ABS(VST2F)                                              016410
  103 D2FDD=AG2*COS(PHIS-ALPHP2-DELG2)                                  016420
      E2FDD=-AG2*SIN(PHIS-ALPHP2-DELG2)                                 016430
      F2FDD=-B2*SIN(PHIS-ALPHP2-BETA2)                                  016440
      X10=1./(D2F*COS(PHI2)-E2F*SIN(PHI2))                              016450
      X11=F2FD-D2FD*SIN(PHI2)-E2FD*COS(PHI2)                            016460
      X12=F2FDD-D2FDD*SIN(PHI2)-E2FDD*COS(PHI2)+DER2F*(-2.*D2FD*        016470
     1COS(PHI2)+2.*E2FD*SIN(PHI2))+DER2F**2*(D2F*SIN(PHI2)+E2F*         016480
     2COS(PHI2))                                                        016490
      Y7=X10*X11                                                        016500
      Y8=X10*X12                                                        016510
   36 IF(T.EQ.0)PHI2PR=PHI2                                             016520
      DDPHI2=PHI2-PHI2PR                                                016530
      IF(DDPHI2.GT.0)DDPHI2=0                                           016540
      PHI2PR=PHI2                                                       016550
C                                                                       016560
C     MESH 1                                                            016570
C                                                                       016580
      DDPHI2P=DDPHI2                                                    016590
      PHI2P=PHI2P+DDPHI2P                                               016600
      IF(PHI2P.LE.PH2PFF)PHI2P=PH2PI                                    016610
      IF(PHI2P.LE.PH2PT)GO TO 39                                        016620
      D1R=-2.*AG1*(AP1*SIN(PHI2P+DELG1-DELP1)+B1*SIN(BETA1+DELG1))      016630
      E1R=-2.*AG1*(AP1*COS(PHI2P+DELG1-DELP1)+B1*COS(BETA1+DELG1))      016640
      F1R=L1**2-AG1**2-AP1**2-B1**2-2.*AP1*B1*COS(PHI2P-BETA1-DELP1)    016650
      ROOT1R=D1R**2+E1R**2-F1R**2                                       016660
      Y1R=D1R+RSGN1R*SQRT(ROOT1R)                                       016670
      X1R=E1R+F1R                                                       016680
      PHI1=2.*ATAN2(Y1R,X1R)                                            016690
      IF(PHI1.LT.0)PHI1=PHI1+2.*PI                                      016700
      PHI1D=PHI1/ZZ                                                     016710
      SLAM1=(B1*SIN(BETA1)+AP1*SIN(PHI2P-DELP1)-AG1*SIN(PHI1-DELG1))/L1 016720
      CLAM1=(B1*COS(BETA1)+AP1*COS(PHI2P-DELP1)-AG1*COS(PHI1-DELG1))/L1 016730
      LAMDA1=ATAN2(SLAM1,CLAM1)                                         016740
```

```
      P2PDOT=PHDOT2
      D1RD=-2.*AG1*AP1*COS(PHI2P+DELG1-DELP1)
      E1RD=2.*AG1*AP1*SIN(PHI2P+DELG1-DELP1)
      F1RD=2.*AP1*B1*SIN(PHI2P-BETA1-DELP1)
      DER1R=(F1RD-D1RD*SIN(PHI1)-E1RD*COS(PHI1))/(D1R*COS(PHI1)-E1R*
     1SIN(PHI1))
      PHDOT1=P2PDOT*DER1R
      VST1R=PHDOT1*(AG1*COS(PHI1-DELG1-LAMDA1)+RHOG1)-PHDOT2*(AP1*
     1COS(PHI2P-DELP1-LAMDA1)-RHOP1)
      IF(VST1R.NE.0)GO TO 104
      S1R=1.
      GO TO 105
  104 S1R=VST1R/ABS(VST1R)
  105 D1RDD=2.*AG1*AP1*SIN(PHI2P+DELG1-DELP1)
      E1RDD=2.*AG1*AP1*COS(PHI2P+DELG1-DELP1)
      F1RDD=2.*AP1*B1*COS(PHI2P-BETA1-DELP1)
      X1=1./(D1R*COS(PHI1)-E1R*SIN(PHI1))
      X2=F1RD-D1RD*SIN(PHI1)-E1RD*COS(PHI1)
      X3=F1RD-D1RDD*SIN(PHI1)-E1RDD*COS(PHI1)+DER1R*(2.*E1RD*SIN(PHI1)
     1-2.*D1RD*COS(PHI1))+DER1R**2*(D1R*SIN(PHI1)+E1R*COS(PHI1))
      Y1=X1*X2
      Y2=X1*X3
      GO TO 40
   39 D1F=-AG1*COS(PHI2P+ALPHP1+DELG1)
      E1F=AG1*SIN(PHI2P+ALPHP1+DELG1)
      F1F=-RHOG1+B1*SIN(PHI2P+ALPHP1-BETA1)
      ROOT1F=D1F**2+E1F**2-F1F**2
      Y1F=D1F+RSGN1F*SQRT(ROOT1F)
      X1F=E1F+F1F
      PHI1=2.*ATAN2(Y1F,X1F)
      IF(PHI1.LT.0)PHI1=PHI1+2.*PI
      PHI1D=PHI1/ZZ
      G1=(AG1*SIN(PHI1-DELG1)-RHOG1*COS(PHI2P+ALPHP1)-B1*SIN(BETA1))
     +/SIN(PHI2P+ALPHP1)
      D1FD=AG1*SIN(PHI2P+ALPHP1+DELG1)
      E1FD=AG1*COS(PHI2P+ALPHP1+DELG1)
      F1FD=B1*COS(PHI2P+ALPHP1-BETA1)
      DER1F=(F1FD-D1FD*SIN(PHI1)-E1FD*COS(PHI1))/(D1F*COS(PHI1)-E1F*
     1SIN(PHI1))
      P2PDOT=PHDOT2
      PHDOT1=P2PDOT*DER1F
      VST1F=PHDOT1*(AG1*SIN(PHI2P+ALPHP1-PHI1+DELG1)+RHOG1)
      IF(VST1F.NE.0)GO TO 107
      S1F=0
      GO TO 108
  107 S1F=VST1F/ABS(VST1F)
  108 D1FDD=AG1*COS(PHI2P+ALPHP1+DELG1)
      E1FDD=-AG1*SIN(PHI2P+ALPHP1+DELG1)
      F1FDD=-B1*SIN(PHI2P+ALPHP1-BETA1)
      X4=1./(D1F*COS(PHI1)-E1F*SIN(PHI1))
      X5=F1FD-D1FD*SIN(PHI1)-E1FD*COS(PHI1)
      X6=F1FDD-D1FDD*SIN(PHI1)-E1FDD*COS(PHI1)+DER1F*(-2.*D1FD*
     1COS(PHI1)+2.*E1FD*SIN(PHI1))+DER1F**2*(D1F*SIN(PHI1)+E1F*
     2COS(PHI1))
      Y3=X4*X5
      Y4=X4*X6
   40 IF(T.EQ.0)PHI1PR=PHI1
```

```
      DDPHI1=PHI1-PHI1PR                                        017320
      IF(DDPHI1.LT.0)DDPHI1=0                                   017330
      PHI1PR=PHI1                                               017340
      IF(T.EQ.0)PHI1TOT=0                                       017350
      PHI1TOT=PHI1TOT+DDPHI1                                    017360
      GAM=PHI1RC+PHI1TOT                                        017370
      RETURN                                                    017380
      END                                                       017390
```

```
      SUBROUTINE TRANS1(RHOG,ALPHP,BETA,FP,AG,B,DELG,Z,PH2PT,PHIT,G)    017400
      PI=3.14159                                                        017410
      CT=(-RHOG*SIN(PH2PT+ALPHP)+B*COS(BETA)+FP*COS(PH2PT+ALPHP))/      017420
     +AG                                                                017430
      ST=(RHOG*COS(PH2PT+ALPHP)+B*SIN(BETA)+FP*SIN(PH2PT+ALPHP))/AG     017440
      PHIT=ATAN2(ST,CT)+DELG                                            017450
      IF(PHIT.LT.O)PHIT=PHIT+2.*PI                                      017460
      PHINEX=PHIT+O.O1*Z                                                017470
      AF=AG*COS(PHINEX-DELG-ALPHP)-B*COS(BETA-ALPHP)                    017480
      BF=-AG*SIN(PHINEX-DELG-ALPHP)+B*SIN(BETA-ALPHP)                   017490
      CF=-RHOG                                                          017500
      ROOTF=AF**2+BF**2-CF**2                                           017510
      Y1F=AF+SQRT(ROOTF)                                                017520
      Y2F=AF-SQRT(ROOTF)                                                017530
      XF=BF+CF                                                          017540
      P2NEX1=2.*ATAN2(Y1F,XF)                                           017550
      P2NEX2=2.*ATAN2(Y2F,XF)                                           017560
      IF(P2NEX1.LT.O.)P2NEX1=P2NEX1+2.*PI                               017570
      IF(P2NEX2.LT.O.)P2NEX2=P2NEX2+2.*PI                               017580
      IF(ABS(P2NEX1-PH2PT).LT.ABS(P2NEX2-PH2PT))GO TO 1                 017590
      P2NEX=P2NEX2                                                      017600
      GO TO 2                                                           017610
    1 P2NEX=P2NEX1                                                      017620
    2 G=(AG*SIN(PHINEX-DELG)-RHOG*COS(P2NEX+ALPHP)-B*SIN(BETA))/SIN(P2NE017630
     1X+ALPHP)                                                          017640
      RETURN                                                            017650
      END                                                               017660
```

```
      SUBROUTINE TRANS2(RHOG,ALPHP,BETA,FP,AG,B,DELG,Z,PHIST,PHIT,G)     017670
      PI=3.141592                                                          017680
      ST=(-RHOG*COS(PHIST-ALPHP)+FP*SIN(PHIST-ALPHP)+B*SIN(BETA))/AG     017690
      CT=(RHOG*SIN(PHIST-ALPHP)+FP*COS(PHIST-ALPHP)+B*COS(BETA))/AG      017700
      PHIT=ATAN2(ST,CT)-DELG                                               017710
      IF(PHIT.LT.O)PHIT=PHIT+2.*PI                                         017720
      PHINEX=PHIT-O.O1*Z                                                   017730
      AF=AG*COS(PHINEX+DELG+ALPHP)-B*COS(BETA+ALPHP)                       017740
      BF=-AG*SIN(PHINEX+DELG+ALPHP)+B*SIN(BETA+ALPHP)                      017750
      CF=RHOG                                                              017760
      ROOTF=AF**2+BF**2-CF**2                                              017770
      Y1F=AF+SQRT(ROOTF)                                                   017780
      Y2F=AF-SQRT(ROOTF)                                                   017790
      XF=BF+CF                                                             017800
      PSNEX1=2.*ATAN2(Y1F,XF)                                              017810
      PSNEX2=2.*ATAN2(Y2F,XF)                                              017820
      IF(PSNEX1.LT.O)PSNEX1=PSNEX1+2.*PI                                   017830
      IF(PSNEX2.LT.O)PSNEX2=PSNEX2+2.*PI                                   017840
      IF(ABS(PSNEX1-PHIST).LT.ABS(PSNEX2-PHIST))GO TO 1                   017850
      PSINEX=PSNEX2                                                        017860
      GO TO 2                                                              017870
    1 PSINEX=PSNEX1                                                        017880
    2 G=(AG*SIN(PHINEX+DELG)+RHOG*COS(PSINEX-ALPHP)-B*SIN(BETA))/SIN(    017890
     +PSINEX-ALPHP)                                                        017900
      RETURN                                                               017910
      END                                                                  017920
```

```
      SUBROUTINE FCT(T,PHI,DPHI)                                         017930
      DIMENSION PHI(2),DPHI(2)                                           017940
      COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,     017950
     +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,  017960
     +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,   017970
     +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,       017980
     +GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,      017990
     +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,     018000
     +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,            018010
     +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2          018020
     +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2                               018030
     +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,          018040
     +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,                           018050
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F 018060
      COMMON/DATA2/KX,KY,OX,OY,OZ,QX,QY,QZ                               018070
      COMMON/DATA5/LU,LL,MU,MU1                                          018080
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,             018090
     +PHI2P,PHI1,PHI2,GAM                                                018100
      COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S       018110
      COMMON/DATA9/AA105,AA106,AA107,AA108,AA109,AA110,AA115,AA116,      018120
     +AA117,AA118,AA119,AA120,AA121,AA122,AA123,AA124,AA125,             018130
     +AA130,AA131,AA132                                                  018140
      COMMON/DATA10/AA9,AA29,AA30,AA31,AA32,AA48,AA49R,AA49F,AA50,AA51,  018150
     +AA60,AA79R,AA79F,AA80,AA81,AA82,AA99,AA100,AA101FR,AA101RR,        018160
     +AA101FF,AA101RF,AA102FR,AA102RR,AA102FF,AA102RF,AA103,AA104,       018170
     +AA111,AA112,AA113,AA114,AA126,AA127,AA128,AA129                    018180
      COMMON/DATA11/AA133,AA134,AA135,AA136,AA137,AA138,AA139,AA140,     018190
     +AA141,AA142,AA143,AA144,AA145,AA146,AA147,AA148,AA149,AA150,       018200
     +AA151,AA152,AA153,AA154,AA155,AA156,AA157,AA158,AA159,AA160,       018210
     +AA161,AA162,AA163,AA164,AA165,AA166,AA167,AA168,AA169,AA170,       018220
     +AA171,AA172,AA173,AA174,AA175,AA176,AA177                          018230
      REAL M1,M2,M3,MP,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,IXS,IYS018240
     +,IZS,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,MU,MU1,LU,LL,LAMBDA,NG1,NG2,    018250
     +NP2,NP3,N,NT,LX1,LY1,LL1,LX2,LY2,LL2,L1,L2,KX,KY                   018260
      CALL KINEM(A,B,ALPHR,PHI,C,PSI,DPSI)                               018270
      CALL AFIVE(T,PHI(1),PHI(2),PSI,DPSI,DELPHI,IPR)                    018280
      CALL ASIX(T,PHI(1),PHI(2),PSI,DPSI,DELPHI,IPR)                     018290
      BETA=PSI+PSIC                                                      018300
      SB=SIN(BETA)                                                       018310
      CB=COS(BETA)                                                       018320
      CG=COS(GAM)                                                        018330
      SG=SIN(GAM)                                                        018340
      IF((PHI1.LE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 1                     018350
      IF((PHI1.GE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 2                     018360
      IF((PHI1.GE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 3                     018370
      IF((PHI1.LE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 4                     018380
    1 W1=AA105                                                           018390
      W2=AA106                                                           018400
      W3=AA107                                                           018410
      W4=AA108                                                           018420
      W5=AA109                                                           018430
      W6=AA110                                                           018440
      GO TO 5                                                            018450
    2 W1=AA120                                                           018460
      W2=AA121                                                           018470
      W3=AA122                                                           018480
      W4=AA123                                                           018490
```

```
      W5=AA124                                                          018500
      W6=AA125                                                          018510
      GO TO 5                                                           018520
    3 W1=AA134                                                          018530
      W2=AA135                                                          018540
      W3=AA136                                                          018550
      W4=AA137                                                          018560
      W5=AA138                                                          018570
      W6=AA139                                                          018580
      GO TO 5                                                           018590
    4 W1=AA148                                                          018600
      W2=AA149                                                          018610
      W3=AA150                                                          018620
      W4=AA151                                                          018630
      W5=AA152                                                          018640
      W6=AA153                                                          018650
    5 DPHI(1)=PHI(2)                                                    018660
      DPHI(2)=1./W1*(-W2*PHI(2)**2-W3*PHI(2)+W4+W5*(OX*SG-OY*CG)+W6*    018670
     1(KX*SB-KY*CB))                                                    018680
      RETURN                                                            018690
      END                                                               018700
```

```
      SUBROUTINE OUTP(T,PHI,DPHI,IHLF,NDIM,PRMT)                        018710
      DIMENSION PHI(2),DPHI(2),PRMT(5)                                  018720
      COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,    018730
     +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY, 018740
     +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,  018750
     +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,      018760
     +GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,     018770
     +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,    018780
     +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,           018790
     +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2         018800
     +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2                              018810
     +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,         018820
     +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,                          018830
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F 018840
      COMMON/ZETA/PSI,TIME,DPSI,GP,PHICUTD                              018850
      COMMON/DATA2/KX,KY,OX,OY,OZ,QX,QY,QZ                              018860
      COMMON/DATA5/LU,LL,MU,MU1                                         018870
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,            018880
     +PHI2P,PHI1,PHI2,GAM                                               018890
      COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S      018900
      COMMON/DATA9/AA105,AA106,AA107,AA108,AA109,AA110,AA115,AA116,     018910
     +AA117,AA118,AA119,AA120,AA121,AA122,AA123,AA124,AA125,            018920
     +AA130,AA131,AA132                                                 018930
      COMMON/DATA10/AA9,AA29,AA30,AA31,AA32,AA48,AA49R,AA49F,AA50,AA51, 018940
     +AA60,AA79R,AA79F,AA80,AA81,AA82,AA99,AA100,AA101FR,AA101RR,       018950
     +AA101FF,AA101RF,AA102FR,AA102RR,AA102FF,AA102RF,AA103,AA104,      018960
     +AA111,AA112,AA113,AA114,AA126,AA127,AA128,AA129                   018970
      COMMON/DATA11/AA133,AA134,AA135,AA136,AA137,AA138,AA139,AA140,    018980
     +AA141,AA142,AA143,AA144,AA145,AA146,AA147,AA148,AA149,AA150,      018990
     +AA151,AA152,AA153,AA154,AA155,AA156,AA157,AA158,AA159,AA160,      019000
     +AA161,AA162,AA163,AA164,AA165,AA166,AA167,AA168,AA169,AA170,      019010
     +AA171,AA172,AA173,AA174,AA175,AA176,AA177                         019020
      REAL M1,M2,M3,MP,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,IXS,IYS019030
     +,IZS,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,MU,MU1,LU,LL,LAMBDA,NG1,NG2,   019040
     +NP2,NP3,N,NT,LX1,LY1,LL1,LX2,LY2,LL2,L1,L2,KX,KY,IPR              019050
      PHID=PHI(1)/ZZ                                                    019060
      DELPHI=PHID-PHIPR                                                 019070
      PHIPR=PHID                                                        019080
      PHITOT=PHITOT+DELPHI                                              019090
      PHIT=PHITOT*ZZ                                                    019100
      DDPHSD=DELPHI                                                     019110
      DDPHIS=DDPHSD*ZZ                                                  019120
      PHIS=PHIS+DDPHIS                                                  019130
      PHISD=PHIS/ZZ                                                     019140
      PHI2D=PHI2/ZZ                                                     019150
      PHI1D=PHI1/ZZ                                                     019160
      CALL KINEM(A,B,ALPHR,PHI,C,PS..DPSI)                              019190
      PSID=PSI/ZZ                                                       019200
      CALL AFIVE(T,PHI(1),PHI(2),PSI,DPSI,DELPHI,IPR)                   019210
      CALL ASIX(T,PHI(1),PHI(2),PSI,DPSI,DELPHI,IPR)                    019220
      BETA=PSI+PSIC                                                     019230
      SB=SIN(BETA)                                                      019240
      CB=COS(BETA)                                                      019250
      SG=SIN(GAM)                                                       019260
      CG=COS(GAM)                                                       019270
C                                                                       019280
C     COMPUTATION OF CONTACT FORCES                                     019290
```

```
C                                                                      019300
      IF((PHI1.LE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 1                   019310
      IF((PHI1.GE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 2                   019320
      IF((PHI1.GE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 3                   019330
      IF((PHI1.LE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 4                   019340
    1 DDPHI=(-AA106*PHI(2)**2-AA107*PHI(2)+AA108+AA109*(OX*SG-OY*CG)   019350
     1+AA110*(KX*SB-KY*CB))/AA105                                      019360
      DPSI2=U*DDPHI+V*PHI(2)**2                                        019370
      F23RR=(AA111*DDPHI+AA112*PHI(2)**2+AA113*PHI(2)+AA114)/AA101RR   019380
      F12RR=(AA115*DDPHI+AA116*PHI(2)**2+AA117*PHI(2)+AA118)/AA79R     019390
      PN=(IZS*DDPHI+AA48*PHI(2)**2+F23RR*AA49R+AA50)/AA51              019400
      IF(F23RR.GT.F23RRMX)F23RRMX=F23RR                                019410
      IF(F12RR.GT.F12RRMX)F12RRMX=F12RR                                019420
      IF(PN.GT.PNMAX)PNMAX=PN                                          019430
      PNPSI=(IPR*DPSI2+AA32*DPSI**2+AA31*DPSI+AA119-MP*RCP*(KX*SB-KY*CB)019440
     1)/AA29                                                           019450
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5                     019460
      WRITE(6,101)T,PHID,PHI(2),G,PSID,DPSI,PHITOT,F23RR,F12RR,PN,PNPSI,019470
     1DDPHI                                                            019480
      GO TO 5                                                          019490
    2 DDPHI=(-AA121*PHI(2)**2-AA122*PHI(2)+AA123+AA124*(OX*SG-OY*CG)   019500
     1+AA125*(KX*SB-KY*CB))/AA120                                      019510
      DPSI2=U*DDPHI+V*PHI(2)**2                                        019520
      F23FF=(AA126*DDPHI+AA127*PHI(2)**2+AA128*PHI(2)+AA129)/AA101FF   019530
      F12FF=(AA130*DDPHI+AA131*PHI(2)**2+AA132*PHI(2)+AA133)/AA79F     019540
      PN=(IZS*DDPHI+AA48*PHI(2)**2+F23FF*AA49F+AA50)/AA51              019550
      IF(F23FF.GT.F23FFMX)F23FFMX=F23FF                                019560
      IF(F12FF.GT.F12FFMX)F12FFMX=F12FF                                019570
      IF(PN.GT.PNMAX)PNMAX=PN                                          019580
      PNPSI=(IPR*DPSI2+AA32*DPSI**2+AA31*DPSI+AA119-MP*RCP*(KX*SB-KY*CB)019590
     1)/AA29                                                           019600
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5                     019610
      WRITE(6,102)T,PHID,PHI(2),G,PSID,DPSI,PHITOT,F23FF,F12FF,PN,PNPSI,019620
     1DDPHI                                                            019630
      GO TO 5                                                          019640
    3 DDPHI=(-AA135*PHI(2)**2-AA136*PHI(2)+AA137+AA138*(OX*SG-OY*CG)   019650
     1+AA139*(KX*SB-KY*CB))/AA134                                      019660
      DPSI2=U*DDPHI+V*PHI(2)**2                                        019670
      F23RF=(AA140*DDPHI+AA141*PHI(2)**2+AA142*PHI(2)+AA143)/AA101RF   019680
      F12RF=(AA144*DDPHI+AA145*PHI(2)**2+AA146*PHI(2)+AA147)/AA79F     019690
      PN=(IZS*DDPHI+AA48*PHI(2)**2+F23RF*AA49R+AA50)/AA51              019700
      IF(F23RF.GT.F23RFMX)F23RFMX=F23RF                                019710
      IF(F12RF.GT.F12RFMX)F12RFMX=F12RF                                019720
      IF(PN.GT.PNMAX)PNMAX=PN                                          019730
      PNPSI=(IPR*DPSI2+AA32*DPSI**2+AA31*DPSI+AA119-MP*RCP*(KX*SB-KY*CB)019740
     +)/AA29                                                           019750
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5                     019760
      WRITE(6,103)T,PHID,PHI(2),G,PSID,DPSI,PHITOT,F23RF,F12RF,PN,PNPSI,019770
     1DDPHI                                                            019780
      GO TO 5                                                          019790
    4 DDPHI=(-AA149*PHI(2)**2-AA150*PHI(2)+AA151+AA152*(OX*SG-OY*CG)   019800
     1+AA153*(KX*SB-KY*CB))/AA148                                      019810
      DPSI2=U*DDPHI+V*PHI(2)**2                                        019820
      F23FR=(AA154*DDPHI+AA155*PHI(2)**2+AA156*PHI(2)+AA157)/AA101FR   019830
      F12FR=(AA158*DDPHI+AA159*PHI(2)**2+AA160*PHI(2)+AA161)/AA79R     019840
      PN=(IZS*DDPHI+AA48*PHI(2)**2+F23FR*AA49F+AA50)/AA51              019850
      IF(F23FR.GT.F23FRMX)F23FRMX=F23FR                                019860
```

```
      IF(F12FR.GT.F12FRMX)F12FRMX=F12FR                                  019870
      IF(PN.GT.PNMAX)PNMAX=PN                                            019880
      PNPSI=(IPR*DPSI2+AA32*DPSI**2+AA31*DPSI+AA119-MP*RCP*(KX*SB-KY*CB)019890
     +)/AA29                                                             019900
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5                       019910
      WRITE(6,104)T,PHID,PHI(2),G,PSID,DPSI,PHITOT,F23FR,F12FR,PN,PNPSI,019920
     1DDPHI                                                              019930
C                                                                        019940
C     TEST FOR CONTINUED COUPLED MOTION                                  019950
C                                                                        019960
    5 IF(PHID.GT.150.)GO TO 6                                            019970
      IF(.NOT.(G.GE.O.AND.PN.GT.O))PRMT(5)=1.                            019980
      GO TO 7                                                            019990
    6 IF(.NOT.(G.LE.O.AND.PN.GT.O))PRMT(5)=1.                            020000
    7 PSID=PSI/ZZ                                                        020010
      IF(PHITOT.LT.PHICUTO)GO TO 8                                       020020
      PRMT(5)=1.                                                         020030
    8 TIME=T                                                             020040
      RETURN                                                             020050
                                                                         020060
C                                                                        020070
C                                                                        020080
C                                                                        020090
  101 FORMAT(6X,*T =*,F8.5,5X,*PHI =*,F7.2,5X,*PHIDOT =*,F7.2,5X,*G =*, 020100
     1F6.4,5X,*PSID =*,F7.2,5X,*PSIDOT =*,F8.2,5X,*PHITOT =*,F7.2/18X,  020110
     2*F23RR =*,F7.4,5X,*F12RR =*,F7.4,5X6X,*PN =*,F7.4,5X,*PNPSI =*,   020120
     3F7.4,5X,*DDPHI =*,E12.4)                                           020130
  102 FORMAT(6X,*T =*,F8.5,5X,*PHI =*,F7.2,5X,*PHIDOT =*,F7.2,5X,*G =*, 020140
     1F6.4,5X,*PSID =*,F7.2,5X,*PSIDOT =*,F8.2,5X,*PHITOT =*,F7.2/18X,  020150
     2*F23FF =*,F7.4,5X,*F12FF =*,F7.4,5X,*PN =*,F7.4,5X,*PNPSI =*,     020160
     3F7.4,5X,*DDPHI =*,E12.4)                                           020170
  103 FORMAT(6X,*T =*,F8.5,5X,*PHI =*,F7.2,5X,*PHIDOT =*,F7.2,5X,*G =*, 020180
     1F6.4,5X,*PSID =*,F7.2,5X,*PSIDOT =*,F8.2,5X,*PHITOT =*,F7.2/18X,  020190
     2*F23RF =*,F7.4,5X,*F12RF =*,F7.4,5X,*PN =*,F7.4,5X,*PNPSI =*,     020200
     3F7.4,5X,*DDPHI =*,E12.4)                                           020210
  104 FORMAT(6X,*T =*,F8.5,5X,*PHI =*,F7.2,5X,*PHIDOT =*,F7.2,5X,*G =*, 020220
     1F6.4,5X,*PSID =*,F7.2,5X,*PSIDOT =*,F8.2,5X,*PHITOT =*,F7.2/18X,  020230
     2*F23FR =*,F7.4,5X,*F12FR= *,F7.4,5X,*PN =*,F7.4,5X,*PNPSI =*,     020240
     3F7.4,5X,*DDPHI =*,E12.4)                                           020250
      END                                                                020260
```

```
      SUBROUTINE FCTF(T,X,DX)                                           020270
      DIMENSION X(4),DX(4)                                              020280
      COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,    020290
     +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY, 020300
     +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIFR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,  020310
     +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,      020320
     +GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,     020330
     +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,    020340
     +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,           020350
     +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2         020360
     +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2                              020370
     +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,         020380
     +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,                          020390
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F 020400
      COMMON/DATA2/KX,KY,DX,DY,DZ,QX,QY,QZ                              020410
      COMMON/DATA5/LU,LL,MU,MU1                                         020420
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,            020430
     +PHI2P,PHI1,PHI2,GAM                                               020440
      COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S      020450
      COMMON/DATA9/AA105,AA106,AA107,AA108,AA109,AA110,AA115,AA116,     020460
     +AA117,AA118,AA119,AA120,AA121,AA122,AA123,AA124,AA125,            020470
     +AA130,AA131,AA132                                                 020480
      COMMON/DATA10/AA9,AA29,AA30,AA31,AA32,AA48,AA49R,AA49F,AA50,AA51, 020490
     +AA60,AA79R,AA79F,AA80,AA81,AA82,AA99,AA100,AA101FR,AA101RR,       020500
     +AA101FF,AA101RF,AA102FR,AA102RR,AA102FF,AA102RF,AA103,AA104,      020510
     +AA111,AA112,AA113,AA114,AA126,AA127,AA128,AA129                   020520
      COMMON/DATA11/AA133,AA134,AA135,AA136,AA137,AA138,AA139,AA140,    020530
     +AA141,AA142,AA143,AA144,AA145,AA146,AA147,AA148,AA149,AA150,      020540
     +AA151,AA152,AA153,AA154,AA155,AA156,AA157,AA158,AA159,AA160,      020550
     +AA161,AA162,AA163,AA164,AA165,AA166,AA167,AA168,AA169,AA170,      020560
     +AA171,AA172,AA173,AA174,AA175,AA176,AA177                         020570
      REAL M1,M2,M3,MP,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,IXS,IYS020580
     +,IZS,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,MU,MU1,LU,LL,LAMBDA,NG1,NG2,   020590
     +NP2,NP3,N,NT,LX1,LY1,LL1,LX2,LY2,LL2,L1,L2,KX,KY,IPR              020600
      CALL AFIVE(T,X(1),X(2),X(3),X(4),DELPHI,IPR)                      020610
      CALL ASIX(T,X(1),X(2),X(3),X(4),DELPHI,IPR)                       020620
      BETA=X(3)+PSIC                                                    020630
      SB=SIN(BETA)                                                      020640
      CB=COS(BETA)                                                      020650
      IF((PHI1.LE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 1                    020660
      IF((PHI1.GE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 2                    020670
      IF((PHI1.GE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 3                    020680
      IF((PHI1.LE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 4                    020690
    1 Z1=AA162                                                          020700
      Z2=AA163                                                          020710
      Z3=AA164                                                          020720
      Z4=AA165                                                          020730
      GO TO 5                                                           020740
    2 Z1=AA166                                                          020750
      Z2=AA167                                                          020760
      Z3=AA168                                                          020770
      Z4=AA169                                                          020780
      GO TO 5                                                           020790
    3 Z1=AA170                                                          020800
      Z2=AA171                                                          020810
      Z3=AA172                                                          020820
      Z4=AA173                                                          020830
```

```
      GO TO 5
    4 Z1=AA174
      Z2=AA175
      Z3=AA176
      Z4=AA177
    5 DX(1)=X(2)
      DX(3)=X(4)
      DX(2)=(-Z2*X(2)**2-Z3*X(2)-Z4)/Z1
      DX(4)=(-AA32*X(4)**2-AA31*X(4)-AA119+MP*RCP*(KX*SB-KY*CB))/IPR
      RETURN
      END
```

```
      SUBROUTINE OUTPF(T,X,DX,IHLF,NDIM2,PRMT)                            020950
      COMMON/DATA2/KX,KY,OX,OY                                            020960
      DIMENSION X(4),DX(4),PRMT(5)                                        020970
      COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,      020980
     +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,   020990
     +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,    021000
     +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,        021010
     +GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,       021020
     +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,      021030
     +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,             021040
     +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2           021050
     +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2                                021060
     +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,           021070
     +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,                            021080
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F   021090
      COMMON/ZETA/PSI,TIME,DPSI,GP,PHICUTD                                021100
      COMMON/DATA5/LU,LL,MU,MU1                                           021110
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,              021120
     +PHI2P,PHI1,PHI2,GAM                                                 021130
      COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S        021140
      COMMON/DATA9/AA105,AA106,AA107,AA108,AA109,AA110,AA115,AA116,       021150
     +AA117,AA118,AA119,AA120,AA121,AA122,AA123,AA124,AA125,              021160
     +AA130,AA131,AA132                                                   021170
      COMMON/DATA10/AA9,AA29,AA30,AA31,AA32,AA48,AA49R,AA49F,AA50,AA51,   021180
     +AA60,AA79R,AA79F,AA80,AA81,AA82,AA99,AA100,AA101FR,AA101RR,         021190
     +AA101FF,AA101RF,AA102FR,AA102RR,AA102FF,AA102RF,AA103,AA104,        021200
     +AA111,AA112,AA113,AA114,AA126,AA127,AA128,AA129                     021210
      COMMON/DATA11/AA133,AA134,AA135,AA136,AA137,AA138,AA139,AA140,      021220
     +AA141,AA142,AA143,AA144,AA145,AA146,AA147,AA148,AA149,AA150,        021230
     +AA151,AA152,AA153,AA154,AA155,AA156,AA157,AA158,AA159,AA160,        021240
     +AA161,AA162,AA163,AA164,AA165,AA166,AA167,AA168,AA169,AA170,        021250
     +AA171,AA172,AA173,AA174,AA175,AA176,AA177                           021260
      REAL M1,M2,M3,MP,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,IXS,IYS021270
     +,IZS,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,MU,MU1,LU,LL,LAMBDA,NG1,NG2,     021280
     +NP2,NP3,N,NT,LX1,LY1,LL1,LX2,LY2,LL2,L1,L2,KX,KY,IPR                021290
      PHID=X(1)/ZZ                                                        021300
      PSID=X(3)/ZZ                                                        021310
      DELPHI=PHID-PHIPR                                                   021320
      PHITOT=PHITOT+DELPHI                                                021330
      PHIT=PHITOT*ZZ                                                      021340
      PHIPR=PHID                                                          021350
      DDPHSD=DELPHI                                                       021360
      DDPHIS=DDPHSD*ZZ                                                    021370
      PHIS=PHIS+DDPHIS                                                    021380
      CALL AFIVE(T,X(1),X(2),X(3),X(4),DELPHI,IPR)                        021390
      CALL ASIX(T,X(1),X(2),X(3),X(4),DELPHI,IPR)                         021400
      BETA=X(3)+PSIC                                                      021410
      SB=SIN(BETA)                                                        021420
      CB=COS(BETA)                                                        021430
      DPSI2=(-AA32*X(4)**2-AA31*X(4)-AA119+MP*RCP*(KX*SB-KY*CB))/IPR      021440
C                                                                         021450
C     COMPUTATION OF CONTACT FORCES                                       021460
C                                                                         021470
      IF((PHI1.LE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 1                      021480
      IF((PHI1.GE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 2                      021490
      IF((PHI1.GE.PHI1T).AND.(PHI2.GE.PHI2T))GO TO 3                      021500
      IF((PHI1.LE.PHI1T).AND.(PHI2.LE.PHI2T))GO TO 4                      021510
```

```
    1 DDPHI=(-AA163*X(2)**2-AA164*X(2)-AA165)/AA162                     021520
      T23RR=-(IZS*DDPHI+AA48*X(2)**2+AA50)/AA49R                        021530
      T12RR=(AA115*DDPHI+AA116*X(2)**2+AA117*X(2)+AA118)/AA79R          021540
      IF(T23RR.GT.T23RRMX)T23RRMX=T23RR                                 021542
      IF(T12RR.GT.T12RRMX)T12RRMX=T12RR                                 021543
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5                      021545
      WRITE(6,101)T,PHID,X(2),PSID,X(4),PHITOT,T23RR,T12RR              021550
  101 FORMAT(6X,*T =*,F8.5,5X,*PHI =*,F7.2,5X,*PHIDOT =*,F7.2,5X,       021560
     +*PSI =*,F7.2,5X,*PSIDOT =*,F8.2,5X,*PHITOT =*,F7.2/20X,*T23RR =*, 021570
     +F7.3,5X,*T12RR =*,F7.3)                                           021580
      GO TO 5                                                           021590
    2 DDPHI=-(AA167*X(2)**2+AA168*X(2)+AA169)/AA166                     021600
      T23FF=-(IZS*DDPHI+AA48*X(2)**2+AA50)/AA49F                        021610
      T12FF=(AA130*DDPHI+AA131*X(2)**2+AA132*X(2)+AA133)/AA79F          021620
      IF(T23FF.GT.T23FFMX)T23FFMX=T23FF                                 021622
      IF(T12FF.GT.T12FFMX)T12FFMX=T12FF                                 021623
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5                      021625
      WRITE(6,102)T,PHID,X(2),PSID,X(4),PHITOT,T23FF,T12FF              021630
  102 FORMAT(6X,*T =*,F8.5,5X,*PHI =*,F7.2,5X,*PHIDOT =*,F7.2,5X,       021640
     +*PSI =*,F7.2,5X,*PSIDOT =*,F8.2,5X,*PHITOT =*,F7.2/20X,*T23FF =*, 021650
     +F7.3,5X,*T12FF =*,F7.3)                                           021660
      GO TO 5                                                           021670
    3 DDPHI=-(AA171*X(2)**2+AA172*X(2)+AA173)/AA170                     021680
      T23RF=-(IZS*DDPHI+AA48*X(2)**2+AA50)/AA49R                        021690
      T12RF=(AA144*DDPHI+AA145*X(2)**2+AA146*X(2)+AA147)/AA79F          021700
      IF(T23RF.GT.T23RFMX)T23RFMX=T23RF                                 021702
      IF(T12RF.GT.T12RFMX)T12RFMX=T12RF                                 021703
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5                      021705
      WRITE(6,103)T,PHID,X(2),PSID,X(4),PHITOT,T23RF,T12RF              021710
  103 FORMAT(6X,*T =*,F8.5,5X,*PHI =*,F7.2,5X,*PHIDOT =*,F7.2,5X,       021720
     +*PSI =*,F7.2,5X,*PSIDOT =*,F8.2,5X,*PHITOT =*,F7.2/20X,*T23RF =*, 021730
     +F7.3,5X,*T12RF =*,F7.3)                                           021740
      GO TO 5                                                           021750
    4 DDPHI=-(AA175*X(2)**2+AA176*X(2)+AA177)/AA174                     021760
      T23FR=-(IZS*DDPHI+AA48*X(2)**2+AA50)/AA49F                        021770
      T12FR=(AA158*DDPHI+AA159*X(2)**2+AA160*X(2)+AA161)/AA79R          021780
      IF(T23FR.GT.T23FRMX)T23FRMX=T23FR                                 021782
      IF(T12FR.GT.T12FRMX)T12FRMX=T12FR                                 021783
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 5                      021785
      WRITE(6,104)T,PHID,X(2),PSID,X(4),PHITOT,T23FR,T12FR              021790
  104 FORMAT(6X,*T =*,F8.5,5X,*PHI =*,F7.2,5X,*PHIDOT =*,F7.2,5X,       021800
     +*PSI =*,F7.2,5X,*PSIDOT =*,F8.2,5X,*PHITOT =*,F7.2/20X,*T23FR =*, 021810
     +F7.3,5X,*T12FR =*,F7.3)                                           021820
C                                                                       021830
C     CHECK FOR CONTINUED FREE MOTION                                   021840
C                                                                       021850
    5 IF(T.EQ.TIME)GO TO 9                                              021855
      F=A*SIN(X(3)+ALPHR)-B*SIN(X(1)-X(3)-ALPHR)-C*SIN(ALPHR)           021860
      PHI1D=PHI1/ZZ                                                     021870
      PHI2D=PHI2/ZZ                                                     021880
      PHISD=PHIS/ZZ                                                     021890
      PHI2PD=PHI2P/ZZ                                                   021900
      GP=A*COS(X(3)+ALPHR)+B*COS(X(1)-X(3)-ALPHR)-C*COS(ALPHR)          021930
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 10                     021935
      WRITE(6,105)F,GP                                                  021940
  105 FORMAT(22X,*F =*,F5.3,3X,*GP =*,F5.3)                             021950
   10 IF(PHID.LT.145..AND.F.GT.0)GO TO 6                                021970
```

```
      IF(PHID.GE.145..AND.F.LT.O)GO TO 7
      PRMT(5)=1.
    6 IF(GP.LT.O)PRMT(5)=1.
      GO TO 8
    7 IF(GP.GT.O)PRMT(5)=1.
    8 TIME=T
      IF(PHITOT.LT.PHICUTD)GO TO 9
      PRMT(5)=1.
    9 RETURN
      END
```

```
      SUBROUTINE IMPACT(PHI,DPHI,PSI,DPSI)                                022080
      COMMON A,B,C,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,      022090
     +IEZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,   022100
     +RZ,EREST,LAMBDA,DELTA,PHITOT,PHIPR,OMEGA,OM2,RC1,PHI1RC,NG1,NG2,    022110
     +NP2,NP3,R1,R2,R3,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,        022120
     +GAMMA3,GAMA4P,GAMMA4,GAMAPP,DELTA2,DELTA3,DELTA4,BETA2,BETA3,       022130
     +RCP,PSIC,S1,S2,S4,S5,DDPHI,DPSI2,PNMAX,PN,ALPHEN,ALPHEX,BETA1,      022140
     +RHOF,RHOF1,RHOF2,RHOF3,S6,DPHI1,DPHI2P,DPHI2,DPHIS,AG1,             022150
     +AP1,AG2,AP2,ALPHP1,ALPHP2,DELG1,DELG2,FP1,FP2,B1,B2,L1,L2           022160
     +,RHOG1,RHOG2,RHOP1,RHOP2,DELP1,DELP2                                022170
     +,F23RRMX,F12RRMX,F23RFMX,F12RFMX,F23FRMX,F12FRMX,F23FFMX,           022180
     +F12FFMX,T23RRMX,T12RRMX,T23RFMX,T12RFMX,                            022190
     +T23FRMX,T12FRMX,T23FFMX,T12FFMX,PHI1R,RSGN1R,RSGN2R,RSGN1F,RSGN2F   022200
      COMMON/DATA6/S2R,S2F,LAMDA2,G2,S1R,S1F,LAMDA1,G1,PHIS,              022210
     +PHI2P,PHI1,PHI2,GAM                                                 022220
      COMMON/DATA8/PHI1T,PHI2T,AONE,BONE,CONE,DONE,U,V,VST,G,P,Q,S        022230
      COMMON/DATA7/DER2R,DER2F,DER1R,DER1F                                022240
      REAL ISTOT,IZS,IZ2,IZZ1,IZZP                                        022250
      AONE=B*COS(PHI-PSI-ALPHR)                                           022260
      DONE=C*COS(ALPHR)+G                                                 022270
      DPHIIN=DPHI                                                         022280
      DPSIIN=DPSI                                                         022290
      IF((PHI1.LE.PHI1T).AND.(PHI2.GE.PHI2T))ISTOT=IZS+IZ2*DER2R**2       022300
     1+IZZ1*DER2R**2*DER1R**2                                             022310
      IF((PHI1.GE.PHI1T).AND.(PHI2.LE.PHI2T))ISTOT=IZS+IZ2*DER2F**2       022320
     1+IZZ1*DER1F**2*DER2F**2                                             022330
      IF((PHI1.GE.PHI1T).AND.(PHI2.GE.PHI2T))ISTOT=IZS+IZ2*DER2R**2       022340
     1+IZZ1*DER1F**2*DER2R**2                                             022350
      IF((PHI1.LE.PHI1T).AND.(PHI2.LE.PHI2T))ISTOT=IZS+IZ2*DER2F**2       022360
     1+IZZ1*DER1R**2*DER2F**2                                             022370
      DPHI=(DPHIIN*(ISTOT*DONE**2-EREST*IZZP*AONE**2)+DPSIIN*IZZP*        022380
     1AONE*DONE*(1.+EREST))/(IZZP*AONE**2+ISTOT*DONE**2)                  022390
      DPSI=(DPHI*AONE-EREST*(DPSIIN*DONE-DPHIIN*AONE))/DONE               022400
      PHID=PHI/ZZ                                                         022410
      PSID=PSI/ZZ                                                         022420
      IF(PHITOT.GT.30..AND.PHITOT.LT.1495.)GO TO 1                        022430
      WRITE(6,2)                                                          022440
      WRITE(6,3)PHID,DPHI,PSID,DPSI,PHITOT                                022450
    1 RETURN                                                              022460
    2 FORMAT(*O*,5X,*IMPACT*)                                             022470
    3 FORMAT(*O*,18X,*PHI =*,F8.3,5X,*PHIDOT =*,F8.3,5X,*PSI =*,F8.3,     022480
     15X,*PSIDOT =*,F8.3,5X,*PHITOT =*,F8.3)                              022490
      END                                                                 022500
```

```
      SUBROUTINE GEAR(CAPRP,CAPRO,RHOG,TCG,AG,DELG)
      BETA=TCG/(2.*CAPRP)
      CAPRPX=-CAPRP*SIN(BETA)
      CAPRPY=CAPRP*COS(BETA)
      A=RHOG*RHOG-CAPRO*CAPRO
      B=RHOG*RHOG-CAPRP*CAPRP
      C=A-B
      D=2.*(CAPRO-CAPRPY)
      E=2.*CAPRPX
      F=-(C*D-CAPRO*E*E)
      G=SQRT((C*D-CAPRO*E*E)**2-(D*D+E*E)*(C*C-A*E*E))
      H=D*D+E*E
      CY1=(F+G)/H
      CY2=(F-G)/H
      IF(CY1.LT.CY2)GO TO 7
      CY=CY2
      GO TO 8
    7 CY=CY1
    8 CX=(C+D*CY)/E
      AG=SQRT(CX*CX+CY*CY)
      DELG=ASIN(CX/AG)
      RETURN
      END
```

```
      SUBROUTINE PINION(RP,RO,RHOP,AP,DELP,ALPHP,FP)           022740
      AP=RP                                                    022750
      DELP=0                                                   022760
      GAMP=ASIN(RHOP/AP)                                       022770
      ALPHP=GAMP-DELP                                          022780
      FP=AP*COS(GAMP)                                          022790
      RETURN                                                   022800
      END                                                      022810
```

```
A=        .22600     B=        .16850     C=        .13242     ALPHEN=  44.0056     ALPHEX=  28.8277

NT= 4.     CONFIG = 2.

EREST= 0.00    LAMBDA=  91.989    N = 22.

NG1 = 41.    NG2 = 29.    NP2 =  6.    NP3 =  6.

CAPRP1 =  .46585    CAPRP2 =  .22835

RP2 =  .06815    RP3 =  .04725

CAPRO1 =  .49560    CAPRO2 =  .24860    RO2 =  .08575    RO3 =  .05950

M1 =     .38510E-04    M2 =     .38500E-05    M3 =     .25920E-05    MP =     .29800E-05

IXX1 =    .1748E-05    IEE1 =    .2324E-05    IZZ1 =    .3462E-05    IXE1 =   -.4256E-06    IZX1 =   -.3446E-06    IEZ1 =   -.4020E-

IX2 =    .4260E-07    IY2 =    .4260E-07    IZ2 =    .4031E-07

IXS =    .3094E-07    IYS =    .3094E-07    IZS =    .1639E-07

IXXP =    .6286E-07    IEEP =    .4827E-07    IZZP =    .7173E-07    IXEP =    .2813E-07    IZXP =  0.        IEZP =  0.

RC1 =  .1000    RCP = 0.0000    RHOP =  .0140    RPM =30000.    PHI1RCD =-113.1200    PSICCD =   0.0000    PHID = 141.0000

PHICUTD = 1595.

MU = .10    MU1 = .10

LU = .177    LL = .177

RHO1 = .04650    RHO2 = .02300    RHO3 = .01700

RHOF1 = .0540    RHOF2 = .0270    RHOF3 = .0200    RHOF = .0180

RHOP1 =   .0176    RHOG1 =   .0440    TCG1 =   .0350
RHOP2 =   .0122    RHOG2 =   .0300    TCG2 =   .0240
R1 = .22500    R2 = .40800    R3 = .36900    R4 = .38800

AG1 = .4610    AP1 = .0682    ALPHP1 =   .261    DELP1 =  0.000    DELG1 =   .057

RHOP1 =   .018    RHOG1 =   .044    FP1 = .0658

AG2 = .2251    AP2 = .0473    ALPHP2 =   .261    DELP2 =  0.000    DELG2 =   .079

RHOP2 =   .012    RHOG2 =   .030    FP2 = .0456

J1 = .95    J2 = .95

RX =    .001    RY =    .001    RZ =   20.000    S8 = -1.

BETA1D = 225.20    BETA2D = 130.04    BETA3D = 104.36
GAMMA2D =-111.76    GAMMA3D =-152.93    GAMMA4D =-187.55
PHI1TD =224.918      PH2PTD =  17.547
PHI1ID =219.978      PH2PID =  51.315      PHI1FD =228.758      PH2PFD = -8.685
PHI2TD =130.328      PHISTD =338.070
PHI2ID =137.642      PHISID =302.743      PHI2FD =125.228      PHISFD =362.743
PHI2I =    .2402E+01    PHI2R1 =    .2031E+01    PHI2R2 =    .2402E+01

COUPLED MOTION
T = 0.00000     PHI = 141.00     PHIDOT =   0.00     G = .0135     PSID =  44.36     PSIDOT =    0.00     PHI1DT =   -.00
```

```
            F23FF = 4.4350   F12FF =17.4328   PN = 1.1551   PNPSI = 1.1551   DDPHI  =  .1335E+07
T = .00000    PHI = 141.00    PHIDOT =   3.52    G = .0135    PSID =  44.36   PSIDOT =   3.31     PHITOT =   .00
            F23FF = 4.4348   F12FF =17.4318   PN = 1.1551   PNPSI = 1.1551   DDPHI  =  .1335E+07
T = .00000    PHI = 141.00    PHIDOT =   5.19    G = .0135    PSID =  44.36   PSIDOT =   4.88     PHITOT =   .00
            F23FF = 4.4345   F12FF =17.4307   PN = 1.1550   PNPSI = 1.1550   DDPHI  =  .1335E+07
T = .00001    PHI = 141.00    PHIDOT =   6.86    G = .0135    PSID =  44.37   PSIDOT =   6.45     PHITOT =   .00
            F23FF = 4.4342   F12FF =17.4296   PN = 1.1549   PNPSI = 1.1549   DDPHI  =  .1335E+07
T = .00001    PHI = 141.00    PHIDOT =  10.19    G = .0134    PSID =  44.37   PSIDOT =   9.59     PHITOT =   .00
            F23FF = 4.4337   F12FF =17.4274   PN = 1.1548   PNPSI = 1.1548   DDPHI  =  .1334E+07
T = .00001    PHI = 141.00    PHIDOT =  13.53    G = .0134    PSID =  44.37   PSIDOT =  12.73     PHITOT =   .00
            F23FF = 4.4331   F12FF =17.4252   PN = 1.1547   PNPSI = 1.1547   DDPHI  =  .1334E+07
T = .00002    PHI = 141.01    PHIDOT =  20.19    G = .0134    PSID =  44.37   PSIDOT =  19.00     PHITOT =   .01
            F23FF = 4.4321   F12FF =17.4205   PN = 1.1545   PNPSI = 1.1545   DDPHI  =  .1332E+07
T = .00002    PHI = 141.02    PHIDOT =  26.85    G = .0134    PSID =  44.38   PSIDOT =  25.27     PHITOT =   .02
            F23FF = 4.4310   F12FF =17.4155   PN = 1.1544   PNPSI = 1.1544   DDPHI  =  .1331E+07
T = .00003    PHI = 141.03    PHIDOT =  40.13    G = .0133    PSID =  44.40   PSIDOT =  37.80     PHITOT =   .03
            F23FF = 4.4291   F12FF =17.4049   PN = 1.1542   PNPSI = 1.1542   DDPHI  =  .1326E+07
T = .00004    PHI = 141.06    PHIDOT =  53.36    G = .0132    PSID =  44.42   PSIDOT =  50.31     PHITOT =   .06
            F23FF = 4.4273   F12FF =17.3934   PN = 1.1543   PNPSI = 1.1543   DDPHI  =  .1321E+07
T = .00005    PHI = 141.10    PHIDOT =  66.53    G = .0131    PSID =  44.45   PSIDOT =  62.80     PHITOT =   .10
            F23FF = 4.4257   F12FF =17.3810   PN = 1.1547   PNPSI = 1.1547   DDPHI  =  .1314E+07
T = .00006    PHI = 141.14    PHIDOT =  79.62    G = .0129    PSID =  44.49   PSIDOT =  75.27     PHITOT =   .14
            F23FF = 4.4243   F12FF =17.3677   PN = 1.1552   PNPSI = 1.1552   DDPHI  =  .1306E+07
T = .00007    PHI = 141.19    PHIDOT =  92.64    G = .0127    PSID =  44.54   PSIDOT =  87.72     PHITOT =   .19
            F23FF = 4.4231   F12FF =17.3537   PN = 1.1560   PNPSI = 1.1560   DDPHI  =  .1297E+07
T = .00008    PHI = 141.24    PHIDOT = 105.54    G = .0125    PSID =  44.59   PSIDOT = 100.14     PHITOT =   .24
            F23FF = 4.4220   F12FF =17.3387   PN = 1.1570   PNPSI = 1.1570   DDPHI  =  .1287E+07
T = .00009    PHI = 141.31    PHIDOT = 118.35    G = .0123    PSID =  44.66   PSIDOT = 112.54     PHITOT =   .31
            F23FF = 4.4209   F12FF =17.3220   PN = 1.1581   PNPSI = 1.1581   DDPHI  =  .1276E+07
T = .00010    PHI = 141.38    PHIDOT = 131.02    G = .0120    PSID =  44.72   PSIDOT = 124.90     PHITOT =   .38
            F23FF = 4.4200   F12FF =17.3047   PN = 1.1595   PNPSI = 1.1595   DDPHI  =  .1263E+07
T = .00011    PHI = 141.46    PHIDOT = 143.57    G = .0117    PSID =  44.80   PSIDOT = 137.24     PHITOT =   .46
            F23FF = 4.4194   F12FF =17.2867   PN = 1.1611   PNPSI = 1.1611   DDPHI  =  .1249E+07
T = .00012    PHI = 141.54    PHIDOT = 155.96    G = .0114    PSID =  44.88   PSIDOT = 149.54     PHITOT =   .54
            F23FF = 4.4190   F12FF =17.2683   PN = 1.1630   PNPSI = 1.1630   DDPHI  =  .1234E+07
T = .00013    PHI = 141.64    PHIDOT = 168.21    G = .0110    PSID =  44.97   PSIDOT = 161.82     PHITOT =   .64
            F23FF = 4.4189   F12FF =17.2493   PN = 1.1651   PNPSI = 1.1651   DDPHI  =  .1218E+07
T = .00014    PHI = 141.74    PHIDOT = 180.28    G = .0106    PSID =  45.07   PSIDOT = 174.05     PHITOT =   .74
            F23FF = 4.4191   F12FF =17.2300   PN = 1.1674   PNPSI = 1.1674   DDPHI  =  .1201E+07
T = .00015    PHI = 141.84    PHIDOT = 192.18    G = .0102    PSID =  45.17   PSIDOT = 186.25     PHITOT =   .84
            F23FF = 4.4196   F12FF =17.2104   PN = 1.1700   PNPSI = 1.1700   DDPHI  =  .1183E+07
T = .00016    PHI = 141.96    PHIDOT = 203.88    G = .0097    PSID =  45.28   PSIDOT = 198.41     PHITOT =   .96
            F23FF = 4.4205   F12FF =17.1906   PN = 1.1729   PNPSI = 1.1729   DDPHI  =  .1164E+07
T = .00017    PHI = 142.08    PHIDOT = 215.40    G = .0093    PSID =  45.40   PSIDOT = 210.54     PHITOT =  1.08
            F23FF = 4.4217   F12FF =17.1706   PN = 1.1760   PNPSI = 1.1760   DDPHI  =  .1144E+07
T = .00018    PHI = 142.20    PHIDOT = 226.69    G = .0088    PSID =  45.52   PSIDOT = 222.62     PHITOT =  1.20
            F23FF = 4.4233   F12FF =17.1505   PN = 1.1794   PNPSI = 1.1794   DDPHI  =  .1122E+07
T = .00019    PHI = 142.34    PHIDOT = 237.78    G = .0083    PSID =  45.65   PSIDOT = 234.67     PHITOT =  1.34
            F23FF = 4.4253   F12FF =17.1304   PN = 1.1831   PNPSI = 1.1831   DDPHI  =  .1100E+07
T = .00020    PHI = 142.48    PHIDOT = 248.61    G = .0077    PSID =  45.79   PSIDOT = 246.67     PHITOT =  1.48
            F23FF = 4.4278   F12FF =17.1105   PN = 1.1871   PNPSI = 1.1871   DDPHI  =  .1077E+07
T = .00021    PHI = 142.62    PHIDOT = 259.23    G = .0071    PSID =  45.93   PSIDOT = 258.64     PHITOT =  1.62
            F23FF = 4.4308   F12FF =17.0907   PN = 1.1913   PNPSI = 1.1913   DDPHI  =  .1052E+07
T = .00022    PHI = 142.77    PHIDOT = 269.58    G = .0065    PSID =  46.09   PSIDOT = 270.54     PHITOT =  1.77
            F23FF = 4.4342   F12FF =17.0712   PN = 1.1959   PNPSI = 1.1959   DDPHI  =  .1027E+07
T = .00023    PHI = 142.93    PHIDOT = 279.69    G = .0059    PSID =  46.24   PSIDOT = 282.42     PHITOT =  1.93
            F23FF = 4.4382   F12FF =17.0521   PN = 1.2007   PNPSI = 1.2007   DDPHI  =  .1001E+07
T = .00024    PHI = 143.09    PHIDOT = 289.51    G = .0053    PSID =  46.41   PSIDOT = 294.23     PHITOT =  2.09
            F23FF = 4.4427   F12FF =17.0335   PN = 1.20[illegible]   PNPSI = 1.2059   DDPHI  =  .9739E+06
[illegible] .00025    PHI = 143.26    PHIDOT = 299.08    G = .0[illegible]    PSID =  46.58   PSIDOT = 306.02     PHITOT = [illegible]
            F23FF = 4.4478   F12FF =17.0155   PN = 1.21[illegible]   PNPSI = 1.2114   DDPHI  =  .9459E+06
T = .00026    PHI = 143.44    PHIDOT = 308.34    G = .0039    PSID =  46.76   PSIDOT = 317.73     PHITOT =  2.44
```

```
            F23FF = 4.4598    F12FF =16.9814    PN = 1.2233     PNPSI = 1.2233    DDPHI =    .8875E+06
T =  .00028     PHI = 143.80     PHIDOT = 325.99    G = .0025     PSID =  47.14    PSIDOT =  341.04      PHITOT =   2.80
            F23FF = 4.4668    F12FF =16.9656    PN = 1.2297     PNPSI = 1.2297    DDPHI =    .8570E+06
T =  .00029     PHI = 143.99     PHIDOT = 334.37    G = .0017     PSID =  47.34    PSIDOT =  352.63      PHITOT =   2.99
            F23FF = 4.4745    F12FF =16.9508    PN = 1.2365     PNPSI = 1.2365    DDPHI =    .8258E+06
T =  .00030     PHI = 144.18     PHIDOT = 342.40    G = .0009     PSID =  47.54    PSIDOT =  364.13      PHITOT =   3.18
            F23RF = 3.9425    F12RF =17.0426    PN = 1.0512     PNPSI = 1.0512    DDPHI =    .5781E+06
T =  .00030     PHI = 144.28     PHIDOT = 345.42    G = .0005     PSID =  47.65    PSIDOT =  368.93      PHITOT =   3.28
            F23RF = 3.9410    F12RF =17.0356    PN = 1.0540     PNPSI = 1.0540    DDPHI =    .5643E+06
T =  .00031     PHI = 144.38     PHIDOT = 348.20    G = .0001     PSID =  47.75    PSIDOT =  373.53      PHITOT =   3.38
            F23RF = 3.9396    F12RF =17.0289    PN = 1.0567     PNPSI = 1.0567    DDPHI =    .5507E+06
T =  .00031     PHI = 144.48     PHIDOT = 350.91    G =-.0003     PSID =  47.86    PSIDOT =  378.11      PHITOT =   3.48
            F23RF = 3.9382    F12RF =17.0225    PN = 1.0595     PNPSI = 1.0595    DDPHI =    .5369E+06

FREE MOTION

T =  .00031     PHI = 209.94     PHIDOT = 350.91     PSI = 315.87     PSIDOT =  378.11     PHITOT =   3.48
              T23RF =   3.319    T12RF = 15.384
T =  .00032     PHI = 210.16     PHIDOT = 417.36     PSI = 316.09     PSIDOT =  374.84     PHITOT =   3.70
              T23RF =   3.310    T12RF = 15.352
                F =-.003    GP =-.016
T =  .00033     PHI = 210.41     PHIDOT = 483.59     PSI = 316.30     PSIDOT =  371.56     PHITOT =   3.96
              T23RF =   3.301    T12RF = 15.321
                F =-.002    GP =-.016
T =  .00034     PHI = 210.71     PHIDOT = 549.93     PSI = 316.51     PSIDOT =  368.28     PHITOT =   4.26
              T23RF =   3.291    T12RF = 15.290
                F =-.001    GP =-.016
T =  .00035     PHI = 211.04     PHIDOT = 616.11     PSI = 316.72     PSIDOT =  365.01     PHITOT =   4.59
              T23RF =   3.281    T12RF = 15.259
                F =-.000    GP =-.015
T =  .00036     PHI = 211.42     PHIDOT = 682.49     PSI = 316.93     PSIDOT =  361.74     PHITOT =   4.96
              T23RF =   3.271    T12RF = 15.229
                F = .001    GP =-.015
VP=   38.147    VS= -80.381

IMPACT

             PHI = 211.416     PHIDOT =-128.781     PSI = 316.932     PSIDOT = 143.825     PHITOT =   4.961
VP=   15.167    VS=  15.167

COUPLED MOTION
T =  .00036     PHI = 211.42     PHIDOT =-128.78    G =-.0141     PSID = 316.33    PSIDOT =  147.17      PHITOT =   4.96
            F23RF = 5.4488    F12RF =19.1531    PN = 2.1131     PNPSI = 2.1131    DDPHI =    .3196E+07
T =  .00037     PHI = 211.35     PHIDOT = -97.07    G =-.0143     PSID = 316.41    PSIDOT =  111.46      PHITOT =   4.90
            F23RF = 5.4496    F12RF =19.1473    PN = 2.1134     PNPSI = 2.1134    DDPHI =    .3146E+07
T =  .00038     PHI = 211.30     PHIDOT = -65.78    G =-.0144     PSID = 316.46    PSIDOT =   75.78      PHITOT =   4.85
            F23RF = 5.4491    F12RF =19.1390    PN = 2.1132     PNPSI = 2.1132    DDPHI =    .3110E+07
T =  .00039     PHI = 211.28     PHIDOT = -34.79    G =-.0145     PSID = 316.50    PSIDOT =   40.17      PHITOT =   4.82
            F23RF = 5.4475    F12RF =19.1284    PN = 2.1127     PNPSI = 2.1127    DDPHI =    .3088E+07
T =  .00040     PHI = 211.26     PHIDOT =  -3.97    G =-.0146     PSID = 316.51    PSIDOT =    4.59      PHITOT =   4.81
            F23RF = 5.4447    F12RF =19.1159    PN = 2.1119     PNPSI = 2.1119    DDPHI =    .3078E+07
T =  .00041     PHI = 211.26     PHIDOT =   3.77    G =-.0146     PSID = 316.51    PSIDOT =   -4.36      PHITOT =   4.81
            F23RF = 3.8799    F12RF =16.8293    PN =  .9203     PNPSI =  .9203    DDPHI =    .7825E+06
T =  .00041     PHI = 211.27     PHIDOT =   7.68    G =-.0146     PSID = 316.51    PSIDOT =   -8.87      PHITOT =   4.81
            F23RF = 3.8779    F12RF =16.8218    PN =  .9197     PNPSI =  .9197    DDPHI =    .7823E+06
T =  .00042     PHI = 211.27     PHIDOT =  11.59    G =-.0146     PSID = 316.50    PSIDOT =  -13.39      PHITOT =   4.81
            F23RF = 3.8760    F12RF =16.8146    PN =  .9191     PNPSI =  .9191    DDPHI =    .7823E+06
T =  .00042     PHI = 211.27     PHIDOT =  15.51    G =-.0145     PSID = 316.50    PSIDOT =  -17.90      PHITOT =   4.82
            F23RF = 3.8742    F12RF =16.8079    PN =  .9186     PNPSI =  .9186    DDPHI =    .7827E+06
T =  .00043     PHI = 211.28     PHIDOT =  23.34    G =-.0145     PSID = 316.49    PSIDOT =  -26.93      PHITOT =   4.83
            F23RF = 3.8708    F12RF =16.7958    PN =  .9176     PNPSI =  .9176    DDPHI =    .7842E+06
```

```
T =   .00045     PHI = 211.32     PHIDOT =  39.07      G =-.0144      PSID = 316.44      PSIDOT =   -44.97      PHITOT =    4.87
              F23RF = 3.8654    F12RF =16.7772      PN =  .9163     PNPSI =  .9163     DDPHI =    .7907E+06
T =   .00046     PHI = 211.34     PHIDOT =  47.00      G =-.0143      PSID = 316.42      PSIDOT =   -53.99      PHITOT =    4.89
              F23RF = 3.8633    F12RF =16.7708      PN =  .9158     PNPSI =  .9158     DDPHI =    .7958E+06
T =   .00047     PHI = 211.37     PHIDOT =  54.99      G =-.0142      PSID = 316.38      PSIDOT =   -63.03      PHITOT =    4.92
              F23RF = 3.8617    F12RF =16.7665      PN =  .9156     PNPSI =  .9156     DDPHI =    .8020E+06
T =   .00048     PHI = 211.41     PHIDOT =  63.03      G =-.0141      PSID = 316.34      PSIDOT =   -72.08      PHITOT =    4.95
              F23RF = 3.8606    F12RF =16.7643      PN =  .9155     PNPSI =  .9155     DDPHI =    .8094E+06
T =   .00049     PHI = 211.45     PHIDOT =  71.17      G =-.0140      PSID = 316.30      PSIDOT =   -81.15      PHITOT =    4.99
              F23RF = 3.8600    F12RF =16.7643      PN =  .9156     PNPSI =  .9156     DDPHI =    .8181E+06
T =   .00050     PHI = 211.49     PHIDOT =  79.39      G =-.0138      PSID = 316.25      PSIDOT =   -90.25      PHITOT =    5.03
              F23RF = 3.8599    F12RF =16.7665      PN =  .9159     PNPSI =  .9159     DDPHI =    .8282E+06
T =   .00051     PHI = 211.54     PHIDOT =  87.72      G =-.0136      PSID = 316.20      PSIDOT =   -99.37      PHITOT =    5.08
              F23RF = 3.8603    F12RF =16.7710      PN =  .9164     PNPSI =  .9164     DDPHI =    .8395E+06
T =   .00052     PHI = 211.59     PHIDOT =  96.17      G =-.0135      PSID = 316.14      PSIDOT =  -108.53      PHITOT =    5.13
              F23RF = 3.8612    F12RF =16.7778      PN =  .9171     PNPSI =  .9171     DDPHI =    .8523E+06
T =   .00053     PHI = 211.65     PHIDOT = 104.75      G =-.0133      PSID = 316.07      PSIDOT =  -117.72      PHITOT =    5.19
              F23RF = 3.8626    F12RF =16.7870      PN =  .9179     PNPSI =  .9179     DDPHI =    .8666E+06
T =   .00054     PHI = 211.71     PHIDOT = 113.48      G =-.0131      PSID = 316.00      PSIDOT =  -126.96      PHITOT =    5.25
              F23RF = 3.8646    F12RF =16.7987      PN =  .9190     PNPSI =  .9190     DDPHI =    .8823E+06
T =   .00055     PHI = 211.78     PHIDOT = 122.38      G =-.0128      PSID = 315.93      PSIDOT =  -136.25      PHITOT =    5.32
              F23RF = 3.8672    F12RF =16.8127      PN =  .9202     PNPSI =  .9202     DDPHI =    .8997E+06
T =   .00056     PHI = 211.85     PHIDOT = 131.46      G =-.0126      PSID = 315.85      PSIDOT =  -145.58      PHITOT =    5.40
              F23RF = 3.8703    F12RF =16.8292      PN =  .9216     PNPSI =  .9216     DDPHI =    .9188E+06
T =   .00057     PHI = 211.93     PHIDOT = 140.74      G =-.0123      PSID = 315.76      PSIDOT =  -154.98      PHITOT =    5.47
              F23RF = 3.8739    F12RF =16.8482      PN =  .9232     PNPSI =  .9232     DDPHI =    .9396E+06
T =   .00058     PHI = 212.01     PHIDOT = 150.23      G =-.0120      PSID = 315.67      PSIDOT =  -164.44      PHITOT =    5.56
              F23RF = 3.8781    F12RF =16.8697      PN =  .9249     PNPSI =  .9249     DDPHI =    .9623E+06
T =   .00059     PHI = 212.10     PHIDOT = 159.96      G =-.0117      PSID = 315.57      PSIDOT =  -173.96      PHITOT =    5.65
              F23RF = 3.8828    F12RF =16.8937      PN =  .9268     PNPSI =  .9268     DDPHI =    .9870E+06
T =   .00060     PHI = 212.19     PHIDOT = 169.94      G =-.0114      PSID = 315.47      PSIDOT =  -183.56      PHITOT =    5.74
              F23RF = 3.8881    F12RF =16.9202      PN =  .9289     PNPSI =  .9289     DDPHI =    .1014E+07
T =   .00061     PHI = 212.29     PHIDOT = 180.21      G =-.0111      PSID = 315.36      PSIDOT =  -193.24      PHITOT =    5.84
              F23RF = 3.8939    F12RF =16.9491      PN =  .9311     PNPSI =  .9311     DDPHI =    .1043E+07
T =   .00062     PHI = 212.40     PHIDOT = 190.77      G =-.0107      PSID = 315.25      PSIDOT =  -202.98      PHITOT =    5.95
              F23RF = 3.9003    F12RF =16.9805      PN =  .9334     PNPSI =  .9334     DDPHI =    .1074E+07
T =   .00063     PHI = 212.51     PHIDOT = 201.66      G =-.0103      PSID = 315.13      PSIDOT =  -212.83      PHITOT =    6.06
              F23RF = 3.9071    F12RF =17.0144      PN =  .9359     PNPSI =  .9359     DDPHI =    .1108E+07
T =   .00064     PHI = 212.63     PHIDOT = 212.90      G =-.0099      PSID = 315.00      PSIDOT =  -222.76      PHITOT =    6.18
              F23RF = 3.9145    F12RF =17.0506      PN =  .9385     PNPSI =  .9385     DDPHI =    .1145E+07
T =   .00065     PHI = 212.76     PHIDOT = 224.52      G =-.0095      PSID = 314.87      PSIDOT =  -232.79      PHITOT =    6.30
              F23RF = 3.9224    F12RF =17.0893      PN =  .9412     PNPSI =  .9412     DDPHI =    .1184E+07
T =   .00066     PHI = 212.89     PHIDOT = 236.53      G =-.0091      PSID = 314.74      PSIDOT =  -242.90      PHITOT =    6.43
              F23RF = 3.9308    F12RF =17.1303      PN =  .9439     PNPSI =  .9439     DDPHI =    .1226E+07
T =   .00067     PHI = 213.03     PHIDOT = 249.00      G =-.0086      PSID = 314.59      PSIDOT =  -253.13      PHITOT =    6.57
              F23RF = 3.9395    F12RF =17.1736      PN =  .9467     PNPSI =  .9467     DDPHI =    .1271E+07
T =   .00068     PHI = 213.17     PHIDOT = 261.92      G =-.0081      PSID = 314.45      PSIDOT =  -263.44      PHITOT =    6.72
              F23RF = 3.9487    F12RF =17.2189      PN =  .9495     PNPSI =  .9495     DDPHI =    .1321E+07
T =   .00069     PHI = 213.33     PHIDOT = 275.36      G =-.0076      PSID = 314.29      PSIDOT =  -273.88      PHITOT =    6.87
              F23RF = 3.9583    F12RF =17.2664      PN =  .9523     PNPSI =  .9523     DDPHI =    .1374E+07
T =   .00070     PHI = 213.49     PHIDOT = 289.34      G =-.0070      PSID = 314.13      PSIDOT =  -284.41      PHITOT =    7.04
              F23RF = 3.9682    F12RF =17.3158      PN =  .9549     PNPSI =  .9549     DDPHI =    .1431E+07
T =   .00071     PHI = 213.66     PHIDOT = 303.93      G =-.0065      PSID = 313.97      PSIDOT =  -295.07      PHITOT =    7.21
              F23RF = 3.9785    F12RF =17.3670      PN =  .9575     PNPSI =  .9575     DDPHI =    .1493E+07
T =   .00072     PHI = 213.84     PHIDOT = 319.14      G =-.0059      PSID = 313.79      PSIDOT =  -305.82      PHITOT =    7.38
              F23RF = 3.9889    F12RF =17.4199      PN =  .9598     PNPSI =  .9598     DDPHI =    .1559E+07
T =   .00073     PHI = 214.03     PHIDOT = 335.06      G =-.0052      PSID = 313.62      PSIDOT =  -316.72      PHITOT =    7.57
              F23RF = 3.9996    F12RF =17.4743      PN =  .9619     PNPSI =  .9619     DDPHI =    .1632E+07
T     .00074     PHI = 214.22     PHIDOT = 351.71      G =-.0[illegible]  PSID = 313.43      PSIDOT =  -327.70      PHITOT =    [illegible]
              F23RF = 4.0104    F12RF =17.5302      PN =  .96[illegible]  PNPSI =  .9637     DDPHI =    .1710E+07
T     .00075     PHI = 214.43     PHIDOT = 369.20      G =-.00[illegible] PSID = 313.24      PSIDOT =  -338.83      PHITOT =    7.97
              F23RF = 4.0213    F12RF =17.5872      PN =  .9650     PNPSI =  .9650     DDPHI =    .1794E+07
```

```
T =  .00077     PHI = 214.87      PHIDOT = 406.84     G =-.0024      PSID = 312.84       PSIDOT = -361.40      PHITOT =    8.42
            F23RF = 4.0430      F12RF =17.7039     PN =  .9661     PNPSI =  .9661      DDPHI =   .1985E+07
T =  .00078     PHI = 215.11      PHIDOT = 427.15     G =-.0016      PSID = 312.63       PSIDOT = -372.83      PHITOT =    8.66
            F23RF = 4.0537      F12RF =17.7632     PN =  .9655     PNPSI =  .9655      DDPHI =   .2092E+07
T =  .00079     PHI = 215.36      PHIDOT = 448.61     G =-.0008      PSID = 312.41       PSIDOT = -384.39      PHITOT =    8.91
            F23RF = 4.0641      F12RF =17.8225     PN =  .9640     PNPSI =  .9640      DDPHI =   .2209E+07
T =  .00080     PHI = 215.63      PHIDOT = 471.24     G = .0001      PSID = 312.19       PSIDOT = -396.00      PHITOT =    9.17
            F23RF = 4.0741      F12RF =17.8817     PN =  .9615     PNPSI =  .9615      DDPHI =   .2336E+07

FREE MOTION

T =  .00080     PHI = 133.81      PHIDOT = 471.24      PSI =   44.18      PSIDOT = -396.00      PHITOT =   9.17
             T23RF =   3.516      T12RF = 16.387
T =  .00081     PHI = 134.10      PHIDOT = 546.94      PSI =   43.95      PSIDOT = -393.23      PHITOT =   9.46
             T23RF =   3.531      T12RF = 16.458
                F = .012    GP = .030
T =  .00082     PHI = 134.44      PHIDOT = 623.02      PSI =   43.73      PSIDOT = -390.47      PHITOT =   9.80
             T23RF =   3.546      T12RF = 16.531
                F = .011    GP = .029
T =  .00083     PHI = 134.81      PHIDOT = 699.83      PSI =   43.50      PSIDOT = -387.71      PHITOT =  10.18
             T23RF =   3.562      T12RF = 16.605
                F = .010    GP = .029
T =  .00084     PHI = 135.24      PHIDOT = 777.09      PSI =   43.28      PSIDOT = -384.96      PHITOT =  10.60
             T23RF =   3.578      T12RF = 16.682
                F = .009    GP = .028
T =  .00085     PHI = 135.71      PHIDOT = 855.15      PSI =   43.06      PSIDOT = -382.22      PHITOT =  11.07
             T23RF =   3.594      T12RF = 16.761
                F = .007    GP = .028
T =  .00086     PHI = 136.22      PHIDOT = 933.69      PSI =  42.84       PSIDOT = -379.49      PHITOT =  11.58
             T23RF =   3.612      T12RF = 16.842
                F = .006    GP = .027
T =  .00087     PHI = 136.78      PHIDOT =1013.14      PSI =   42.63      PSIDOT = -376.76      PHITOT =  12.14
             T23RF =   3.630      T12RF = 16.926
                F = .004    GP = .026
T =  .00088     PHI = 137.38      PHIDOT =1093.09      PSI =   42.41      PSIDOT = -374.04      PHITOT =  12.74
             T23RF =   3.648      T12RF = 17.012
                F = .003    GP = .025
T =  .00089     PHI = 138.03      PHIDOT =1174.05      PSI =   42.20      PSIDOT = -371.33      PHITOT =  13.39
             T23RF =   3.668      T12RF = 17.102
                F = .001    GP = .024
T =  .00090     PHI = 138.72      PHIDOT =1255.54      PSI =   41.99      PSIDOT = -368.63      PHITOT =  14.09
             T23RF =   3.689      T12RF = 17.194
                F =-.001    GP = .023
VP= -43.452   VS= 128.111

IMPACT

           PHI = 138.724     PHIDOT =  65.162     PSI =  41.987      PSIDOT =  56.407      PHITOT =  14.088
VP=   6.649   VS=   6.649

COUPLED MOTION
T =  .00090     PHI = 138.72      PHIDOT =  65.16     G = .0221      PSID =  42.30       PSIDOT =   57.07      PHITOT =   14.09
            F23RF = 4.4646      F12RF =19.3304     PN = 1.1945     PNPSI = 1.1945      DDPHI =   .1679E+07
T =  .00091     PHI = 138.77      PHIDOT =  81.98     G = .0219      PSID =  42.34       PSIDOT =   71.89      PHITOT =   14.13
            F23RF = 4.4913      F12RF =19.4383     PN = 1.2036     PNPSI = 1.2036      DDPHI =   .1686E+07
T =  .00092     PHI = 138.82      PHIDOT =  98.86     G = .0217      PSID =  42.38       PSIDOT =   86.83      PHITOT =   14.18
            F23RF = 4.5187      F12RF =19.5483     PN = 1.2133     PNPSI = 1.2133      DDPHI =   .1692E+07
T =  .00093     PHI = 138.88      PHIDOT = 115.80     G = .0215      PSID =  42.44       PSIDOT =  101.89      PHITOT =   14.24
            F23RF = 4.5466      F12RF =19.6603     PN = 1.2235     PNPSI = 1.2235      DDPHI =   .1696E+07
T =  .00094     PHI = 138.95      PHIDOT = 132.76     G = .0212      PSID =  42.50       PSIDOT =  117.06      PHITOT =   14.31
            F23RF = 4.5752      F12RF =19.7743     PN = 1.2342     PNPSI = 1.2342      DDPHI =   .1699E+07
T =  .00095     PHI = 139.02      PHIDOT = 149.76     G = .0209      PSID =  42.57       PSIDOT =  132.06      PHITOT =   14.40
```

```
             T23RR =   3.912     T12RR = 15.814
T =   .09200   PHI = 134.18      PHIDOT = 687.27     PSI =  43.89    PSIDOT = -496.69    PHITOT =1580.45
             T23RR =   3.894     T12RR = 15.751
               F = .012   GP = .030
T =   .09201   PHI = 134.60      PHIDOT = 779.25     PSI =  43.61    PSIDOT = -493.52    PHITOT =1580.87
             T23RR =   3.877     T12RR = 15.693
               F = .011   GP = .029
T =   .09202   PHI = 135.07      PHIDOT = 870.91     PSI =  43.33    PSIDOT = -490.34    PHITOT =1581.34
             T23RR =   3.863     T12RR = 15.642
               F = .009   GP = .029
T =   .09203   PHI = 135.59      PHIDOT = 962.19     PSI =  43.05    PSIDOT = -487.14    PHITOT =1581.87
             T23RR =   3.849     T12RR = 15.597
               F = .007   GP = .028
T =   .09204   PHI = 136.17      PHIDOT =1053.23     PSI =  42.77    PSIDOT = -483.93    PHITOT =1582.44
             T23RR =   3.838     T12RR = 15.559
               F = .006   GP = .027
T =   .09205   PHI = 136.80      PHIDOT =1143.98     PSI =  42.49    PSIDOT = -480.71    PHITOT =1583.07
             T23RR =   3.828     T12RR = 15.527
               F = .004   GP = .026
T =   .09206   PHI = 137.48      PHIDOT =1234.60     PSI =  42.22    PSIDOT = -477.48    PHITOT =1583.76
             T23RR =   3.821     T12RR = 15.503
               F = .002   GP = .025
T =   .09207   PHI = 138.22      PHIDOT =1325.01     PSI =  41.94    PSIDOT = -474.24    PHITOT =1584.49
             T23RR =   3.816     T12RR = 15.486
               F = .000   GP = .024
T =   .09208   PHI = 139.00      PHIDOT =1415.38     PSI =  41.67    PSIDOT = -470.99    PHITOT =1585.27
             T23RR =   3.812     T12RR = 15.476
               F =-.002   GP = .022
VP= -55.487   VS= 142.459

   IMPACT

               PHI = 139.001     PHIDOT =  18.438    PSI =  41.674   PSIDOT =  15.752    PHITOT =1585.273
VP=   1.856   VS=   1.856

   COUPLED MOTION
T =   .09208   PHI = 139.00      PHIDOT =  18.44     G = .0210    PSID =  42.54    PSIDOT =  16.28    PHITOT =1585.27
            F23RR = 4.2364      F12RR =16.0074         PN = 1.1910    PNPSI = 1.1910    DDPHI =   .1597E+07
T =   .09209   PHI = 139.02      PHIDOT =  34.27     G = .0210    PSID =  42.56    PSIDOT =  30.28    PHITOT =1585.29
            F23RR = 4.1936      F12RR =15.8548         PN = 1.1780    PNPSI = 1.1780    DDPHI =   .1570E+07
T =   .09210   PHI = 139.04      PHIDOT =  49.84     G = .0209    PSID =  42.58    PSIDOT =  44.06    PHITOT =1585.31
            F23RR = 4.1505      F12RR =15.7011         PN = 1.1651    PNPSI = 1.1651    DDPHI =   .1543E+07
T =   .09211   PHI = 139.07      PHIDOT =  65.12     G = .0208    PSID =  42.61    PSIDOT =  57.63    PHITOT =1585.35
            F23RR = 4.1073      F12RR =15.5467         PN = 1.1523    PNPSI = 1.1523    DDPHI =   .1513E+07
T =   .09212   PHI = 139.11      PHIDOT =  80.10     G = .0206    PSID =  42.64    PSIDOT =  70.97    PHITOT =1585.39
            F23RR = 4.0638      F12RR =15.3915         PN = 1.1396    PNPSI = 1.1396    DDPHI =   .1483E+07
T =   .09213   PHI = 139.16      PHIDOT =  94.77     G = .0204    PSID =  42.69    PSIDOT =  84.09    PHITOT =1585.44
            F23RR = 4.0203      F12RR =15.2358         PN = 1.1271    PNPSI = 1.1271    DDPHI =   .1451E+07
T =   .09214   PHI = 139.22      PHIDOT = 109.11     G = .0202    PSID =  42.74    PSIDOT =  96.98    PHITOT =1585.50
            F23RR = 3.9767      F12RR =15.0797         PN = 1.1147    PNPSI = 1.1147    DDPHI =   .1418E+07
T =   .09215   PHI = 139.29      PHIDOT = 123.11     G = .0200    PSID =  42.80    PSIDOT = 109.65    PHITOT =1585.56
            F23RR = 3.9330      F12RR =14.9233         PN = 1.1025    PNPSI = 1.1025    DDPHI =   .1383E+07
T =   .09216   PHI = 139.36      PHIDOT = 136.77     G = .0197    PSID =  42.87    PSIDOT = 122.09    PHITOT =1585.64
            F23RR = 3.8893      F12RR =14.7668         PN = 1.0904    PNPSI = 1.0904    DDPHI =   .1348E+07
T =   .09217   PHI = 139.45      PHIDOT = 150.08     G = .0194    PSID =  42.94    PSIDOT = 134.30    PHITOT =1585.72
            F23RR = 3.8457      F12RR =14.6102         PN = 1.0784    PNPSI = 1.0784    DDPHI =   .1312E+07
T =   .09218   PHI = 139.54      PHIDOT = 163.01     G = .0190    PSID =  43.02    PSIDOT = 146.28    PHITOT =1585.81
            F23RR = 3.8020      F12RR =14.4538         PN = 1.0665    PNPSI = 1.0665    DDPHI =   .1275E+07
T     .09219   PHI = 139.63      PHIDOT = 175.58     G = .0       PSID =  43.1     PSIDOT = 158.03    PHITOT =158
            F23RR = 3.7585      F12RR =14.2977         PN     0548    PNPSI = 1.0548    DDPHI =   .1238E+07
T     .09220   PHI = 139.74      PHIDOT = 187.77     G = .0       PSID =  43.20    PSIDOT = 169.55    PHITOT =1586.01
            F23RR = 3.7152      F12RR =14.1420         PN = 1.0431    PNPSI = 1.0431    DDPHI =   .1200E+07
```

```
T =  .09222     PHI = 139.97     PHIDOT = 210.99     G = .0174     PSID =  43.41     PSIDOT =  191.89     PHITOT =1586.24
              F23RR = 3.6290     F12RR =13.8323        PN = 1.0203       PNPSI = 1.0203     DDPHI =    .1122E+07
T =  .09223     PHI = 140.09     PHIDOT = 222.01     G = .0169     PSID =  43.52     PSIDOT =  202.71     PHITOT =1586.36
              F23RR = 3.5862     F12RR =13.6787        PN = 1.0091       PNPSI = 1.0091     DDPHI =    .1082E+07
T =  .09224     PHI = 140.22     PHIDOT = 232.63     G = .0164     PSID =  43.64     PSIDOT =  213.29     PHITOT =1586.49
              F23RR = 3.5438     F12RR =13.5260        PN =  .9980       PNPSI =  .9980     DDPHI =    .1042E+07
T =  .09225     PHI = 140.36     PHIDOT = 242.86     G = .0159     PSID =  43.77     PSIDOT =  223.65     PHITOT =1586.63
              F23RR = 3.5017     F12RR =13.3745        PN =  .9871       PNPSI =  .9871     DDPHI =    .1002E+07
T =  .09226     PHI = 140.50     PHIDOT = 252.68     G = .0154     PSID =  43.90     PSIDOT =  233.78     PHITOT =1586.77
              F23RR = 3.4599     F12RR =13.2243        PN =  .9763       PNPSI =  .9763     DDPHI =    .9621E+06
T =  .09227     PHI = 140.65     PHIDOT = 262.10     G = .0148     PSID =  44.03     PSIDOT =  243.68     PHITOT =1586.92
              F23RR = 3.4186     F12RR =13.0754        PN =  .9656       PNPSI =  .9656     DDPHI =    .9217E+06
T =  .09228     PHI = 140.80     PHIDOT = 271.11     G = .0142     PSID =  44.18     PSIDOT =  253.34     PHITOT =1587.07
              F23RR = 3.3777     F12RR =12.9281        PN =  .9551       PNPSI =  .9551     DDPHI =    .8814E+06
T =  .09229     PHI = 140.96     PHIDOT = 279.72     G = .0136     PSID =  44.32     PSIDOT =  262.79     PHITOT =1587.23
              F23RR = 3.3373     F12RR =12.7826        PN =  .9448       PNPSI =  .9448     DDPHI =    .8411E+06
T =  .09230     PHI = 141.12     PHIDOT = 287.93     G = .0130     PSID =  44.48     PSIDOT =  272.01     PHITOT =1587.39
              F23RR = 3.2975     F12RR =12.6388        PN =  .9346       PNPSI =  .9346     DDPHI =    .8009E+06
T =  .09231     PHI = 141.29     PHIDOT = 295.74     G = .0124     PSID =  44.63     PSIDOT =  281.00     PHITOT =1587.56
              F23RR = 3.2582     F12RR =12.4971        PN =  .9246       PNPSI =  .9246     DDPHI =    .7609E+06
T =  .09232     PHI = 141.46     PHIDOT = 303.15     G = .0117     PSID =  44.80     PSIDOT =  289.78     PHITOT =1587.73
              F23RR = 3.1268     F12RR =12.3559        PN =  .9198       PNPSI =  .9198     DDPHI =    .7283E+06
T =  .09233     PHI = 141.63     PHIDOT = 310.22     G = .0110     PSID =  44.97     PSIDOT =  298.39     PHITOT =1587.91
              F23RR = 3.0893     F12RR =12.2188        PN =  .9093       PNPSI =  .9093     DDPHI =    .6876E+06
T =  .09234     PHI = 141.81     PHIDOT = 316.91     G = .0103     PSID =  45.14     PSIDOT =  306.80     PHITOT =1588.09
              F23RR = 3.0524     F12RR =12.0841        PN =  .8990       PNPSI =  .8990     DDPHI =    .6474E+06
T =  .09235     PHI = 142.00     PHIDOT = 323.20     G = .0096     PSID =  45.32     PSIDOT =  314.98     PHITOT =1588.27
              F23RR = 3.0163     F12RR =11.9520        PN =  .8890       PNPSI =  .8890     DDPHI =    .6076E+06
T =  .09236     PHI = 142.18     PHIDOT = 329.09     G = .0089     PSID =  45.50     PSIDOT =  322.94     PHITOT =1588.46
              F23RR = 2.9808     F12RR =11.8225        PN =  .8791       PNPSI =  .8791     DDPHI =    .5683E+06
T =  .09237     PHI = 142.37     PHIDOT = 334.59     G = .0081     PSID =  45.69     PSIDOT =  330.68     PHITOT =1588.65
              F23RR = 2.9461     F12RR =11.6959        PN =  .8694       PNPSI =  .8694     DDPHI =    .5295E+06
T =  .09238     PHI = 142.57     PHIDOT = 339.71     G = .0074     PSID =  45.88     PSIDOT =  338.21     PHITOT =1588.84
              F23RR = 2.9122     F12RR =11.5721        PN =  .8599       PNPSI =  .8599     DDPHI =    .4914E+06
T =  .09239     PHI = 142.76     PHIDOT = 344.44     G = .0066     PSID =  46.08     PSIDOT =  345.53     PHITOT =1589.04
              F23RR = 2.8792     F12RR =11.4514        PN =  .8506       PNPSI =  .8506     DDPHI =    .4539E+06
T =  .09240     PHI = 142.96     PHIDOT = 348.81     G = .0058     PSID =  46.28     PSIDOT =  352.65     PHITOT =1589.23
              F23RR = 2.8470     F12RR =11.3340        PN =  .8416       PNPSI =  .8416     DDPHI =    .4171E+06
T =  .09241     PHI = 143.16     PHIDOT = 352.81     G = .0050     PSID =  46.48     PSIDOT =  359.55     PHITOT =1589.44
              F23RR = 2.8157     F12RR =11.2198        PN =  .8327       PNPSI =  .8327     DDPHI =    .3810E+06
T =  .09242     PHI = 143.37     PHIDOT = 356.46     G = .0042     PSID =  46.69     PSIDOT =  366.26     PHITOT =1589.64
              F23RR = 2.7854     F12RR =11.1091        PN =  .8242       PNPSI =  .8242     DDPHI =    .3456E+06
T =  .09243     PHI = 143.57     PHIDOT = 359.75     G = .0034     PSID =  46.90     PSIDOT =  372.78     PHITOT =1589.84
              F23RR = 2.7560     F12RR =11.0019        PN =  .8159       PNPSI =  .8159     DDPHI =    .3111E+06
T =  .09244     PHI = 143.78     PHIDOT = 362.71     G = .0025     PSID =  47.12     PSIDOT =  379.10     PHITOT =1590.05
              F23RR = 2.7276     F12RR =10.8984        PN =  .8078       PNPSI =  .8078     DDPHI =    .2775E+06
T =  .09245     PHI = 143.99     PHIDOT = 365.33     G = .0017     PSID =  47.33     PSIDOT =  385.24     PHITOT =1590.26
              F23RR = 2.7002     F12RR =10.7987        PN =  .8000       PNPSI =  .8000     DDPHI =    .2447E+06
T =  .09246     PHI = 144.20     PHIDOT = 367.63     G = .0009     PSID =  47.56     PSIDOT =  391.19     PHITOT =1590.47
              F23RR = 2.6739     F12RR =10.7029        PN =  .7925       PNPSI =  .7925     DDPHI =    .2128E+06
T =  .09247     PHI = 144.41     PHIDOT = 369.61     G =-.0000     PSID =  47.78     PSIDOT =  396.97     PHITOT =1590.68
              F23RR = 2.6487     F12RR =10.6111        PN =  .7853       PNPSI =  .7853     DDPHI =    .1818E+06

FREE MOTION

T =  .09247     PHI = 209.86     PHIDOT = 369.61     PSI = 315.79     PSIDOT =  396.97     PHITOT =1590.68
              T23RR =   2.219     T12RR =   9.621
T =  .09248     PHI = 210.09     PHIDOT = 415.82     PSI = 316.02     PSIDOT =  393.39     PHITOT =1590.91
              T23RR =   2.203     T12RR =   9.559
                F =-.003   GP =-.017
T =  .09249     PHI = 210.34     PHIDOT = 461.55     PSI = 316.24     PSIDOT =  389.81     PHITOT =1591.16
```

```
T =  .09250     PHI = 210.62      PHIDOT = 506.76     PSI = 316.47      PSIDOT =  386.25      PHITOT =1591.43
             T23RR =  2.175       T12RR =  9.453
                F =-.001    GP =-.016
T =  .09251     PHI = 210.92      PHIDOT = 551.55     PSI = 316.69      PSIDOT =  382.69      PHITOT =1591.74
             T23RR =  2.164       T12RR =  9.409
                F =-.000    GP =-.015
T =  .09252     PHI = 211.25      PHIDOT = 595.88     PSI = 316.91      PSIDOT =  379.14      PHITOT =1592.07
             T23RR =  2.154       T12RR =  9.371
                F = .001    GP =-.015
VP=  39.272   VS= -70.357

IMPACT

             PHI = 211.248      PHIDOT =-160.209     PSI = 316.905      PSIDOT = 182.620      PHITOT =1592.066
VP=  18.916   VS=  18.916

COUPLED MOTION
T =  .09252     PHI = 211.25      PHIDOT =-160.21     G =-.0146     PSID = 316.53     PSIDOT =  185.33     PHITOT =1592.07
           F23RR = 3.8644      F12RR =12.1610        PN = 1.6835     PNPSI = 1.6835     DDPHI =   .2638E+07
T =  .09253     PHI = 211.16      PHIDOT =-134.13     G =-.0149     PSID = 316.62     PSIDOT =  156.11     PHITOT =1591.98
           F23RR = 3.8530      F12RR =12.1139        PN = 1.6814     PNPSI = 1.6814     DDPHI =   .2581E+07
T =  .09254     PHI = 211.09      PHIDOT =-108.57     G =-.0152     PSID = 316.71     PSIDOT =  126.99     PHITOT =1591.91
           F23RR = 3.8425      F12RR =12.0712        PN = 1.6792     PNPSI = 1.6792     DDPHI =   .2534E+07
T =  .09255     PHI = 211.04      PHIDOT = -83.42     G =-.0153     PSID = 316.77     PSIDOT =   97.97     PHITOT =1591.86
           F23RR = 3.8330      F12RR =12.0328        PN = 1.6770     PNPSI = 1.6770     DDPHI =   .2497E+07
T =  .09256     PHI = 211.00      PHIDOT = -58.61     G =-.0155     PSID = 316.82     PSIDOT =   69.03     PHITOT =1591.82
           F23RR = 3.8244      F12RR =11.9990        PN = 1.6750     PNPSI = 1.6750     DDPHI =   .2469E+07
T =  .09257     PHI = 210.97      PHIDOT = -34.02     G =-.0156     PSID = 316.85     PSIDOT =   40.15     PHITOT =1591.79
           F23RR = 3.8169      F12RR =11.9696        PN = 1.6731     PNPSI = 1.6731     DDPHI =   .2450E+07
T =  .09258     PHI = 210.96      PHIDOT =  -9.59     G =-.0156     PSID = 316.86     PSIDOT =   11.33     PHITOT =1591.78
           F23RR = 3.8104      F12RR =11.9449        PN = 1.6713     PNPSI = 1.6713     DDPHI =   .2439E+07
T =  .09258     PHI = 210.96      PHIDOT =  -6.54     G =-.0156     PSID = 316.86     PSIDOT =    7.73     PHITOT =1591.78
           F23RR = 3.8097      F12RR =11.9422        PN = 1.6711     PNPSI = 1.6711     DDPHI =   .2438E+07
T =  .09258     PHI = 210.96      PHIDOT =  -3.50     G =-.0156     PSID = 316.87     PSIDOT =    4.13     PHITOT =1591.78
           F23RR = 3.8090      F12RR =11.9395        PN = 1.6709     PNPSI = 1.6709     DDPHI =   .2438E+07
T =  .09259     PHI = 210.96      PHIDOT =  -1.97     G =-.0156     PSID = 316.87     PSIDOT =    2.33     PHITOT =1591.78
           F23RR = 3.8086      F12RR =11.9381        PN = 1.6708     PNPSI = 1.6708     DDPHI =   .2437E+07
T =  .09259     PHI = 210.96      PHIDOT =   -.45     G =-.0156     PSID = 316.87     PSIDOT =     .53     PHITOT =1591.78
           F23RR = 3.8083      F12RR =11.9368        PN = 1.6707     PNPSI = 1.6707     DDPHI =   .2437E+07
T =  .09259     PHI = 210.96      PHIDOT =   -.07     G =-.0156     PSID = 316.87     PSIDOT =     .08     PHITOT =1591.78
           F23RR = 3.8082      F12RR =11.9365        PN = 1.6707     PNPSI = 1.6707     DDPHI =   .2437E+07
T =  .09259     PHI = 210.96      PHIDOT =    .10     G =-.0156     PSID = 316.87     PSIDOT =    -.11     PHITOT =1591.78
           F23RR = 2.3842      F12RR = 9.7003        PN =  .5759     PNPSI =  .5759     DDPHI =   .3620E+06
T =  .09259     PHI = 210.96      PHIDOT =    .15     G =-.0156     PSID = 316.87     PSIDOT =    -.18     PHITOT =1591.78
           F23RR = 2.3840      F12RR = 9.6997        PN =  .5758     PNPSI =  .5758     DDPHI =   .3620E+06
T =  .09259     PHI = 210.96      PHIDOT =    .21     G =-.0156     PSID = 316.87     PSIDOT =    -.25     PHITOT =1591.78
           F23RR = 2.3839      F12RR = 9.6990        PN =  .5758     PNPSI =  .5758     DDPHI =   .3619E+06
T =  .09259     PHI = 210.96      PHIDOT =    .32     G =-.0156     PSID = 316.87     PSIDOT =    -.38     PHITOT =1591.78
           F23RR = 2.3835      F12RR = 9.6978        PN =  .5757     PNPSI =  .5757     DDPHI =   .3618E+06
T =  .09259     PHI = 210.96      PHIDOT =    .44     G =-.0156     PSID = 316.87     PSIDOT =    -.51     PHITOT =1591.78
           F23RR = 2.3832      F12RR = 9.6966        PN =  .5755     PNPSI =  .5755     DDPHI =   .3617E+06
T =  .09259     PHI = 210.96      PHIDOT =    .66     G =-.0156     PSID = 316.87     PSIDOT =    -.78     PHITOT =1591.78
           F23RR = 2.3825      F12RR = 9.6941        PN =  .5753     PNPSI =  .5753     DDPHI =   .3615E+06
T =  .09259     PHI = 210.96      PHIDOT =    .89     G =-.0156     PSID = 316.87     PSIDOT =   -1.05     PHITOT =1591.78
           F23RR = 2.3818      F12RR = 9.6917        PN =  .5750     PNPSI =  .5750     DDPHI =   .3613E+06
T =  .09259     PHI = 210.96      PHIDOT =   1.11     G =-.0156     PSID = 316.87     PSIDOT =   -1.32     PHITOT =1591.78
           F23RR = 2.3811      F12RR = 9.6893        PN =  .5748     PNPSI =  .5748     DDPHI =   .3612E+06
T =  .09259     PHI = 210.96      PHIDOT =   1.34     G =-.0156     PSID = 316.87     PSIDOT =   -1.58     PHITOT =1591.78
           F23RR = 2.3805      F12RR = 9.6869        PN   .5746     PNPSI =  .5746     DDPHI =   .3610E+06
T   .09259     PHI = 210.96      PHIDOT =   1.79     G =-.0             PSID = 316.87     PSIDOT =   -2.11     PHITOT =159
           F23RR = 2.3792      F12RR = 9.6822        PN   .5741     PNPSI =  .5741     DDPHI =   .3606E+06
T =  .09259     PHI = 210.96      PHIDOT =   2.24     G =-.0156     PSID = 316.87     PSIDOT =   -2.65     PHITOT =1591.78
```

```
              F23RR = 2.3753    F12RR = 9.6686       PN =  .5727    PNPSI =  .5727    DDPHI =    .3596E+06
T =  .09260     PHI = 210.96     PHIDOT =   4.04   G =-.0156    PSID = 316.86    PSIDOT =   -4.77    PHITOT =1591.78
              F23RR = 2.3729    F12RR = 9.6599       PN =  .5719    PNPSI =  .5719    DDPHI =    .3590E+06
T =  .09260     PHI = 210.96     PHIDOT =   4.94   G =-.0156    PSID = 316.86    PSIDOT =   -5.83    PHITOT =1591.78
              F23RR = 2.3706    F12RR = 9.6515       PN =  .5710    PNPSI =  .5710    DDPHI =    .3584E+06
T =  .09260     PHI = 210.96     PHIDOT =   5.83   G =-.0156    PSID = 316.86    PSIDOT =   -6.89    PHITOT =1591.78
              F23RR = 2.3683    F12RR = 9.6435       PN =  .5702    PNPSI =  .5702    DDPHI =    .3579E+06
T =  .09261     PHI = 210.96     PHIDOT =   7.62   G =-.0156    PSID = 316.86    PSIDOT =   -9.00    PHITOT =1591.78
              F23RR = 2.3641    F12RR = 9.6284       PN =  .5686    PNPSI =  .5686    DDPHI =    .3570E+06
T =  .09261     PHI = 210.97     PHIDOT =   9.40   G =-.0156    PSID = 316.86    PSIDOT =  -11.10    PHITOT =1591.78
              F23RR = 2.3602    F12RR = 9.6147       PN =  .5672    PNPSI =  .5672    DDPHI =    .3562E+06
T =  .09262     PHI = 210.97     PHIDOT =  11.18   G =-.0156    PSID = 316.85    PSIDOT =  -13.20    PHITOT =1591.79
              F23RR = 2.3566    F12RR = 9.6022       PN =  .5658    PNPSI =  .5658    DDPHI =    .3557E+06
T =  .09262     PHI = 210.97     PHIDOT =  12.96   G =-.0156    PSID = 316.85    PSIDOT =  -15.29    PHITOT =1591.79
              F23RR = 2.3535    F12RR = 9.5911       PN =  .5646    PNPSI =  .5646    DDPHI =    .3553E+06
T =  .09263     PHI = 210.98     PHIDOT =  16.51   G =-.0155    PSID = 316.84    PSIDOT =  -19.47    PHITOT =1591.80
              F23RR = 2.3482    F12RR = 9.5727       PN =  .5625    PNPSI =  .5625    DDPHI =    .3551E+06
T =  .09264     PHI = 210.99     PHIDOT =  20.06   G =-.0155    PSID = 316.83    PSIDOT =  -23.64    PHITOT =1591.81
              F23RR = 2.3443    F12RR = 9.5597       PN =  .5608    PNPSI =  .5608    DDPHI =    .3556E+06
T =  .09265     PHI = 211.00     PHIDOT =  23.62   G =-.0155    PSID = 316.81    PSIDOT =  -27.82    PHITOT =1591.82
              F23RR = 2.3419    F12RR = 9.5520       PN =  .5596    PNPSI =  .5596    DDPHI =    .3568E+06
T =  .09266     PHI = 211.02     PHIDOT =  27.20   G =-.0154    PSID = 316.80    PSIDOT =  -31.99    PHITOT =1591.84
              F23RR = 2.3409    F12RR = 9.5495       PN =  .5589    PNPSI =  .5589    DDPHI =    .3587E+06
T =  .09267     PHI = 211.03     PHIDOT =  30.80   G =-.0154    PSID = 316.78    PSIDOT =  -36.18    PHITOT =1591.85
              F23RR = 2.3414    F12RR = 9.5524       PN =  .5586    PNPSI =  .5586    DDPHI =    .3613E+06
T =  .09268     PHI = 211.05     PHIDOT =  34.43   G =-.0153    PSID = 316.75    PSIDOT =  -40.40    PHITOT =1591.87
              F23RR = 2.3433    F12RR = 9.5605       PN =  .5587    PNPSI =  .5587    DDPHI =    .3647E+06
T =  .09269     PHI = 211.07     PHIDOT =  38.10   G =-.0152    PSID = 316.73    PSIDOT =  -44.63    PHITOT =1591.89
              F23RR = 2.3466    F12RR = 9.5739       PN =  .5593    PNPSI =  .5593    DDPHI =    .3689E+06
T =  .09270     PHI = 211.10     PHIDOT =  41.81   G =-.0151    PSID = 316.70    PSIDOT =  -48.90    PHITOT =1591.92
              F23RR = 2.3513    F12RR = 9.5926       PN =  .5604    PNPSI =  .5604    DDPHI =    .3738E+06
T =  .09271     PHI = 211.12     PHIDOT =  45.58   G =-.0151    PSID = 316.67    PSIDOT =  -53.21    PHITOT =1591.94
              F23RR = 2.3575    F12RR = 9.6164       PN =  .5619    PNPSI =  .5619    DDPHI =    .3794E+06
T =  .09272     PHI = 211.15     PHIDOT =  49.41   G =-.0150    PSID = 316.64    PSIDOT =  -57.56    PHITOT =1591.97
              F23RR = 2.3650    F12RR = 9.6455       PN =  .5639    PNPSI =  .5639    DDPHI =    .3858E+06
T =  .09273     PHI = 211.18     PHIDOT =  53.30   G =-.0149    PSID = 316.61    PSIDOT =  -61.97    PHITOT =1592.00
              F23RR = 2.3739    F12RR = 9.6796       PN =  .5662    PNPSI =  .5662    DDPHI =    .3930E+06
T =  .09274     PHI = 211.21     PHIDOT =  57.27   G =-.0148    PSID = 316.57    PSIDOT =  -66.43    PHITOT =1592.03
              F23RR = 2.3842    F12RR = 9.7188       PN =  .5691    PNPSI =  .5691    DDPHI =    .4010E+06
T =  .09275     PHI = 211.24     PHIDOT =  61.33   G =-.0146    PSID = 316.53    PSIDOT =  -70.96    PHITOT =1592.06
              F23RR = 2.3959    F12RR = 9.7631       PN =  .5723    PNPSI =  .5723    DDPHI =    .4099E+06
T =  .09276     PHI = 211.28     PHIDOT =  65.48   G =-.0145    PSID = 316.49    PSIDOT =  -75.56    PHITOT =1592.10
              F23RR = 2.4089    F12RR = 9.8123       PN =  .5760    PNPSI =  .5760    DDPHI =    .4195E+06
T =  .09277     PHI = 211.32     PHIDOT =  69.73   G =-.0144    PSID = 316.44    PSIDOT =  -80.24    PHITOT =1592.14
              F23RR = 2.4232    F12RR = 9.9664       PN =  .5801    PNPSI =  .5801    DDPHI =    .4300E+06
T =  .09278     PHI = 211.36     PHIDOT =  74.08   G =-.0142    PSID = 316.40    PSIDOT =  -85.00    PHITOT =1592.18
              F23RR = 2.4388    F12RR = 9.9253       PN =  .5846    PNPSI =  .5846    DDPHI =    .4414E+06
T =  .09279     PHI = 211.40     PHIDOT =  78.56   G =-.0141    PSID = 316.35    PSIDOT =  -89.86    PHITOT =1592.22
              F23RR = 2.4557    F12RR = 9.9890       PN =  .5895    PNPSI =  .5895    DDPHI =    .4537E+06
T =  .09280     PHI = 211.45     PHIDOT =  83.17   G =-.0139    PSID = 316.29    PSIDOT =  -94.80    PHITOT =1592.27
              F23RR = 2.4738    F12RR =10.0574       PN =  .5948    PNPSI =  .5948    DDPHI =    .4669E+06
T =  .09281     PHI = 211.50     PHIDOT =  87.91   G =-.0138    PSID = 316.24    PSIDOT =  -99.85    PHITOT =1592.32
              F23RR = 2.4932    F12RR =10.1303       PN =  .6005    PNPSI =  .6005    DDPHI =    .4811E+06
T =  .09282     PHI = 211.55     PHIDOT =  92.80   G =-.0136    PSID = 316.18    PSIDOT = -105.01    PHITOT =1592.37
              F23RR = 2.5138    F12RR =10.2076       PN =  .6066    PNPSI =  .6066    DDPHI =    .4963E+06
T =  .09283     PHI = 211.61     PHIDOT =  97.84   G =-.0134    PSID = 316.12    PSIDOT = -110.29    PHITOT =1592.42
              F23RR = 2.5355    F12RR =10.2894       PN =  .6130    PNPSI =  .6130    DDPHI =    .5125E+06
T =  .09284     PHI = 211.66     PHIDOT = 103.06   G =-.0132    PSID = 316.05    PSIDOT = -115.68    PHITOT =1592.48
              F23RR = 2.5583    F12RR =10.3754       PN =  .6198    PNPSI =  .6198    DDPHI =    .5297E+06
T =  .09285     PHI = 211.72     PHIDOT = 108.45   G =-.0130    PSID = 315.99    PSIDOT = -121.20    PHITOT =1592.54
              F23RR = 2.5823    F12RR =10.4655       PN =  .6269    PNPSI =  .6269    DDPHI =    .5481E+06
T =  .09286     PHI = 211.79     PHIDOT = 114.03   G =-.0128    PSID = 315.91    PSIDOT = -126.85    PHITOT =1592.61
```

```
                F23RR = 2.6334    F12RR =10.6578          PN =  .6422    PNPSI =  .6422    DDPHI =    .5884E+06
T =   .09288      PHI = 211.93      PHIDOT = 125.81      G =-.0123     PSID = 315.76     PSIDOT = -138.57      PHITOT =1592.74
                F23RR = 2.6604    F12RR =10.7597          PN =  .6503    PNPSI =  .6503    DDPHI =    .6103E+06
T =   .09289      PHI = 212.00      PHIDOT = 132.03      G =-.0121     PSID = 315.68     PSIDOT = -144.64      PHITOT =1592.82
                F23RR = 2.6884    F12RR =10.8652          PN =  .6586    PNPSI =  .6586    DDPHI =    .6337E+06
T =   .09290      PHI = 212.08      PHIDOT = 138.49      G =-.0118     PSID = 315.60     PSIDOT = -150.87      PHITOT =1592.89
                F23RR = 2.7174    F12RR =10.9743          PN =  .6673    PNPSI =  .6673    DDPHI =    .6584E+06
T =   .09291      PHI = 212.16      PHIDOT = 145.21      G =-.0115     PSID = 315.51     PSIDOT = -157.26      PHITOT =1592.98
                F23RR = 2.7472    F12RR =11.0867          PN =  .6761    PNPSI =  .6761    DDPHI =    .6845E+06
T =   .09292      PHI = 212.24      PHIDOT = 152.20      G =-.0113     PSID = 315.42     PSIDOT = -163.82      PHITOT =1593.06
                F23RR = 2.7778    F12RR =11.2023          PN =  .6853    PNPSI =  .6853    DDPHI =    .7122E+06
T =   .09293      PHI = 212.33      PHIDOT = 159.47      G =-.0110     PSID = 315.32     PSIDOT = -170.53      PHITOT =1593.15
                F23RR = 2.8092    F12RR =11.3210          PN =  .6946    PNPSI =  .6946    DDPHI =    .7416E+06
T =   .09294      PHI = 212.43      PHIDOT = 167.05      G =-.0106     PSID = 315.22     PSIDOT = -177.43      PHITOT =1593.24
                F23RR = 2.8413    F12RR =11.4426          PN =  .7041    PNPSI =  .7041    DDPHI =    .7726E+06
T =   .09295      PHI = 212.52      PHIDOT = 174.94      G =-.0103     PSID = 315.12     PSIDOT = -184.49      PHITOT =1593.34
                F23RR = 2.8741    F12RR =11.5670          PN =  .7138    PNPSI =  .7138    DDPHI =    .8056E+06
T =   .09296      PHI = 212.63      PHIDOT = 183.18      G =-.0100     PSID = 315.01     PSIDOT = -191.75      PHITOT =1593.44
                F23RR = 2.9075    F12RR =11.6939          PN =  .7236    PNPSI =  .7236    DDPHI =    .8404E+06
T =   .09297      PHI = 212.73      PHIDOT = 191.77      G =-.0096     PSID = 314.90     PSIDOT = -199.18      PHITOT =1593.55
                F23RR = 2.9416    F12RR =11.8233          PN =  .7336    PNPSI =  .7336    DDPHI =    .8774E+06
T =   .09298      PHI = 212.85      PHIDOT = 200.75      G =-.0092     PSID = 314.78     PSIDOT = -206.81      PHITOT =1593.66
                F23RR = 2.9761    F12RR =11.9549          PN =  .7436    PNPSI =  .7436    DDPHI =    .9165E+06
T =   .09299      PHI = 212.96      PHIDOT = 210.12      G =-.0088     PSID = 314.66     PSIDOT = -214.62      PHITOT =1593.78
                F23RR = 3.0112    F12RR =12.0886          PN =  .7537    PNPSI =  .7537    DDPHI =    .9581E+06
T =   .09300      PHI = 213.09      PHIDOT = 219.93      G =-.0084     PSID = 314.54     PSIDOT = -222.64      PHITOT =1593.91
                F23RR = 3.0466    F12RR =12.2242          PN =  .7638    PNPSI =  .7638    DDPHI =    .1002E+07
T =   .09301      PHI = 213.22      PHIDOT = 230.19      G =-.0080     PSID = 314.41     PSIDOT = -230.85      PHITOT =1594.03
                F23RR = 3.0824    F12RR =12.3616          PN =  .7739    PNPSI =  .7739    DDPHI =    .1049E+07
T =   .09302      PHI = 213.35      PHIDOT = 240.94      G =-.0075     PSID = 314.27     PSIDOT = -239.26      PHITOT =1594.17
                F23RR = 3.1186    F12RR =12.5004          PN =  .7839    PNPSI =  .7839    DDPHI =    .10    +07
T =   .09303      PHI = 213.49      PHIDOT = 252.20      G =-.0070     PSID = 314.13     PSIDOT = -247.88        ITOT =1594.31
                F23RR = 3.1549    F12RR =12.6406          PN =  .7939    PNPSI =  .7939    DDPHI =    .11     07
T =   .09304      PHI = 213.64      PHIDOT = 264.01      G =-.0065     PSID = 313.99     PSIDOT = -256.70        ITOT =1594.46
                F23RR = 3.1914    F12RR =12.7819          PN =  .8037    PNPSI =  .8037    DDPHI =    .12     07
T =   .09305      PHI = 213.79      PHIDOT = 276.40      G =-.0060     PSID = 313.84     PSIDOT = -265.72        ITOT =1594.61
                F23RR = 3.2281    F12RR =12.9242          PN =  .8133    PNPSI =  .8133    DDPHI =    .1268E+07
T =   .09306      PHI = 213.96      PHIDOT = 289.41      G =-.0055     PSID = 313.68     PSIDOT = -274.96      PHITOT =1594.77
                F23RR = 3.2648    F12RR =13.0672          PN =  .8226    PNPSI =  .8226    DDPHI =    .1332E+07
T =   .09307      PHI = 214.13      PHIDOT = 303.08      G =-.0049     PSID = 313.52     PSIDOT = -284.40      PHITOT =1594.94
                F23RR = 3.3015    F12RR =13.2107          PN =  .8316    PNPSI =  .8316    DDPHI =    .1401E+07
T =   .09308      PHI = 214.30      PHIDOT = 317.47      G =-.0043     PSID = 313.36     PSIDOT = -294.05      PHITOT =1595.12
                F23RF = 3.3241    F12RF =13.3020      PN =  .8360    PNPSI =  .8360     DDPHI =    .1467E+07

F23RRMX =   7.81    F12RRMX = 24.62

F23RFMX =   7.36    F12RFMX = 27.26

F23FRMX =   8.52    F12FRMX = 24.80

F23FFMX =   8.03    F12FFMX = 26.51

T23RRMX =   5.01    T12RRMX = 19.92

T23RFMX =   4.70    T12RFMX = 21.58

T23FRMX =   5.25    T12FRMX = 20.05

    FMX =   4.96    T12FFMX = 20.88

P  X =  3.13
```

DISTRIBUTION LIST

Commander
Armament Research, Development and Engineering Center
U.S. Army Armament, Munitions and Chemical Command
ATTN: SMCAR-IMI-I (3)
SMCAR-GCL
SMCAR-AEF-C (8)
SMCAR-FSA
Picatinny Arsenal, NJ 07806-5000

Administrator
Defense Technical Information Center
ATTN: Accessions Division (12)
Cameron Station
Alexandria, VA 22304-6145

Director
U.S. Army Material Systems Analysis Activity
ATTN: AMXSY-MP
Aberdeen Proving Ground, MD 21005-5066

Commander
Chemical/Biological Defense Agency
U.S. Army Armament, Munitions and Chemical Command
ATTN: AMSCB-CII, Library
Aberdeen Proving Ground, MD 21010-5423

Director
U.S. Army Edgewood Research, Development and Engineering Center
ATTN: SCBRD-RTT (Aerodynamics Technical Team)
Aberdeen Proving Ground, MD 21010-5423

Director
U.S. Army Research Laboratory
ATTN: AMSRL-OP-CI-B, Technical Library
Aberdeen Proving Ground, MD 21005-5066

Chief
Benet Weapons Laboratory, CCAC
Armament Research, Development and Engineering Center
U.S. Army Armament, Munitions and Chemical Command
ATTN: SMCAR-CCB-TL
Watervliet, NY 12189-5000

Director
U.S. Army TRADOC Analysis Command-WSMR
ATTN: ATRC-WSS-R
White Sands Missile Range, NM 88002

Commander
USA ARL
ATTN: Library
SMCAR-AEF-T, J. Beard
2800 Powder Mill Road
Adelphi, MD 20783